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THE CHARACTERISTICS OF THE GROUND VORTEX AND ITS EFFECT ON THE AERODYNAMICS OF THE STOL CONFIGURATION

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ABSTRACT

The interaction of the free stream velocity on the wall jet formed by the impingement of deflected engine thrust results in a rolled up vortex which exerts sizable forces on a STOL airplane configuration. Some data suggests that the boundary layer under the free stream ahead of the configuration may be important in determining the extent of travel of the wall jet into the oncoming stream. This paper examines and discusses the early studies of the ground vortex and compares those results to some later data obtained with a moving model over a fixed ground board. The effect of the ground vortex on the aerodynamic characteristics is also discussed.

SYMBOLS

BP	Butt Plane
C_L	Lift Coefficient $Lift/q_0S$
C_p	Pressure Coefficient $\Delta P/q_0S$
C_μ	Blowing Coefficient $\dot{M}V_j/qS$
d	Nozzle diameter
e_x	Longitudinal distance between jet centerlines
e_y	Lateral distance between jet centerlines
h	Height above ground
$\dot{M}$	Jet mass flow
q_n	Jet dynamic pressure
q_0	Freestream dynamic pressure
S	Reference area
V_e	Equivalent velocity V_∞/V_j
V_j	Jet velocity
V_∞	Freestream velocity
x	Longitudinal distance
X'	Forward extent of ground vortex
y	Lateral distance
z	Vertical distance
$(W/\ell)_j$	Jet aspect ratio
ΔP	Local pressure - ambient pressure
δ	Jet deflection

INTRODUCTION

When a high velocity jet impinges on the ground the jet will form a wall jet. This wall jet will flow along the ground until it is stopped by some outside force. This force may be a second jet, in which case the two wall jets will be deflected off the ground and upward onto the airplane creating a fountain effect. The outside force may be only the ground friction, as in the case of a single jet with no free stream velocity. The wall jet continues along the ground until the forward energy is dissipated by friction.

The third case and the one which is of interest here is that case in which the jet is exhausted from a moving vehicle and impinges on the ground, splits into a wall jet, and spreads along the ground. A portion of the wall jet flows in the same direction as the free stream velocity and, thereby, behaves similar to the single jet without free stream case. The remainder of the jet flows forward into the oncoming free stream and interacts with the free stream to form the ground vortex. It is this portion of the jet and the interaction with the free stream which can result in very sizable suckdown loads and moments on a STOL airplane configuration. The forward extent of the wall jet into the free stream air flow can be related to the relative velocities of the two interacting airstreams. The forward extent will also depend on the angle at which the jet strikes the ground and the height at which the jet is exhausted toward the ground. The angle at which the jet is directed in reality determines the amount of the flow along any ground path. A jet directed aft of the vertical will allow most of the flow to propagate away from the oncoming air while a jet directed into the free stream, such as a thrust reverser, will direct more of the energy into the path of the oncoming stream. Most of the existing data are for the vertical jet condition and, therefore, most of this paper will deal with this condition. A simple expression to account for the angle relationship has been developed and will be discussed.

DISCUSSION

Ground Vortex Formation and Characteristics: The ground vortex is created by that portion of the wall jet which is opposed by the free stream velocity. As seen in Figure 1, the forward portion of the wall jet is rolled into a type of vortex and is directed back onto the wall jet. In truth, this flow is not a real vortex, but rather, a redirection of the flow direction, at least in the single jet configuration as pictured. A jet flap configuration, with a large span nozzle tends to form a rear boundary to the vortex and to result in a more concentrated vortex. With an axisymmetric, round nozzle and jet the vortex is not bound at the rear and is allowed to flow away from the airplane with the free stream. As demonstrated in Figure 1, a vertical (90 degree) jet is directed from the vehicle toward the ground. The jet impacts the ground and a radial wall jet is formed. The wall jet portion which is directed into the free stream is retarded and rolled back forming the ground vortex. The reversed flow then moves with or parallel to the free stream. This flow field wills create negative pressures on the ground and on the underside of the vehicle.

A typical jet centerline pressure distribution is presented in Figure 2. The figure shows a jet at a height less than the critical height above which a vortex would not be formed. The jet from the nozzle will begin to curve into the free stream flow direction and would impact the ground at an angle slightly less than the initial jet angle depending on the height of the nozzle. The jet upon impact will form a radial wall jet as as shown in Figure 1 and flow along the ground. That portion of the wall jet directed into the oncoming airstream will form the ground vortex. The ground pressure distribution is also depicted in Figure 2. A positive pressure is seen on the ground at the point of impact and a negative ground pressure is seen in the area influenced by the ground vortex. This negative pressure will, at least at the lower heights, be reflected onto the lower surface of the airplane configuration directly above the vortex. As seen in the figure the negative pressure region attains maximum negative value at some distance ahead of the impact point and then the negative pressure decreases and, in fact, becomes slightly greater than local static pressure at some point ahead of the vortex. The point of zero delta static pressure has been established as depicting the forward edge of the vortex flow field. This zero pressure point is used in the correlations.

A third important characteristic of the ground vortex is seen in Figure 3. The radial wall jet extends into the free stream a distance related to the energy of the wall jet in that direction. The forward component of energy is reduced as the radial angle moves away from the directly ahead. The shape of the ground vortex is therefore seen as a curved or a horseshoe shaped profile. Figure 3 shows that for these particular conditions, the centerline vortex extends 2.5 nozzle diameters ahead of the nozzle while at a lateral position of three diameters away from the nozzle the forward extent of the vortex is only about one half of a diameter ahead oh the nozzle centerline. The implications of the curved vortex leading edge are significant. The most significant are the asymmetric loads induced on an airplane wings under certain yawed conditions. Since the vortex profile is seen to be symmetric about the free stream centerline, yawing of the vehicle can result in one wing in the influence of the vortex flow field while the opposite wing is forward of the that influence. This condition where one wing is in the influence of the vortex while the other is relatively unaffected can result in large rolling moments into the yawed wing.

Review of Early Data Base: There are several early studies which have investigated the extent and characteristics of the ground vortex. Many of these were done to investigate the effects of the ground flow on the dust and debris and reingestion characteristics due to the vortex. Unfortunately, the early data base as well as some of the later data did not utilize sufficient instrumentation to link the vortex to the aerodynamic lift losses. The studies of the ground vortex tend to be limited to flow field measurements and the aerodynamic tests tend not to properly define the ground vortex. References 1 through 4 fall in the first category. These experimental studies explored the ground vortex formation and investigated the forward travel of the vortex leading edge and all four dealt with with round jets exhausting toward a fixed ground board. The test configurations primarily dealt with isolated jets. Reference 1, Colin and Olivari, investigated the effect of a single vertical jet exhausting at four nozzle diameters above a fixed ground board. Ground board pressure distributions were recorded. Figure 4 presents the ground board pressures in the region of the vortex. These data were obtained at very low nozzle pressure ratios, approximately 1.05, and with a jet velocity of about 265 feet per second. A vortex penetration of approximately 8.5 nozzle diameters is shown at a velocity ratio of 0.10. The data indicate a maximum negative pressure coefficient of approximately -1.7 on the ground at all velocity ratios.

Reference 2, by Abbott, represents a different test technique. Abbott utilized a moving model over a fixed ground board. Abbott's moving model was at the end of a rotating arm and data consisted of photographs of the dust cloud. Abbott's results indicated considerably less forward travel of the ground vortex compared to other tests with a fixed model and fixed ground board, References 3 and 4 offer other measurements of a fixed model over a fixed board and are based on ground pressure instrumentation as was Colin and Olivari. These data present extremes in ground boundary layers. Schwantes, Reference 3, simulated a wind over the ground and produced a thick ground boundary layer, while, Weber and Gay in Reference 4 appeared to utilize a relatively short ground board which would limit the boundary layer thickness. Figure 5 presents a comparison of the ground vortex forward penetration from these references. The penetration from the moving model data is approximately 30 percent less than that shown from References 1 and 3 while the short ground board data from Reference 4 is seen to be between the the data from References 1 and 3 and that of Reference 2.

The data presented in Reference 5 and extensively summarized in Reference 6 and to a lessor extent in References 7 and 8 was obtained from a wind tunnel test of a generic, deflected thrust STOL model configuration. This test provided the first data to investigate the vortex characteristics and relate these to the model loads. The model, shown in Figure 6, was tested with a fixed ground board at varying heights from very near the ground, one nozzle height to free air. The model utilized several nozzle configurations and provided comparisons for an isolated nozzle and a nozzle in presence to a blocking plate and a lifting airplane wing. Nozzle configurations consisting of round and rectangular with aspect ratios of 4 and .25 were tested. Single and multiple nozzle configurations were also tested. Instrumentation included ground board pressures and a model force balance. From these data it is possible to determine the height at which the vortex forms and the extent of the vortex penetration into the free stream air mass. The aerodynamic forces can be related to the vortex characteristics. These tests at velocity ratios of 0.1 and 0.2 were done for a choked nozzle pressure ratio, approximately 1.80. Velocity ratios of 0.1 to 0.2 were obtained by altering tunnel velocity. In order to test a velocity ratio of 0.3, nozzle pressure ratio was reduced.

Represenative ground board pressures are presented in Figures 7 and 8 at a velocity ratio of 0.1. Figure 7 presents the isolated jet results while Figure 8 presents the results with a 10d blocking plate located at the nozzle exit and parallel to the ground. The nozzle exits at the center of the plate for these data. The results shown in Figure 8 indicate that at heights less than approximately 4 diameters the vortex is trapped under the plate and the forward travel is restricted resulting in an increased negative pressure.

The forward projection of the ground vortex has been correlated as a function of height and is reasonably accounted for by the following equation;

$$\frac{X'}{d} = \frac{h}{d}\tan(\delta-90) + \left(.75 - 1.75\left(\frac{h}{d}\right)^{2.5}\left(\frac{W}{\ell}\right)_j^{.3} V_e^{3.25}\left[1 - \sin(\delta-90)\right]\right)\frac{\left(\frac{\delta}{90}\right)^2}{V_e}$$

The correlation of all nozzle configuration data from Reference 5 is shown in Figure 9. The correlation utilizing the above equation to account for nozzle aspect ratio and angle shows relatively good agreement for all data including that with the blocking plates. The summary of data from Reference 5 is compared to that from References 1 through 4 in Figure 10. The penetration of the vortex on the nozzle centerline is slightly less than that from References 1 and 3 but somewhat greater than that of Weber and Gay, Reference 4, and approximately 30 percent greater than shown by Abbott's moving model data, Reference 2.

The comparison of the maximum negative pressure from References 1 and 5, Figures 4 and 7, show the data from Reference 5, taken at a nozzle pressure ratio of 1.8 are significantly higher than that from Reference 1, obtained at a nozzle pressure ratio of approximately 1.05. The pressure ratio may account for the difference in the negative pressure observed under the vortex. However, data more recently obtained at NASA, Langley Research Center (LaRC) may be indicative of another explanation for these differences in the ground board pressures.

The NASA data was obtained with a moving model and a fixed ground board. The ground board had a 4 degree ramp and a long flat section parallel to the model path. Details of this test are discussed in Paulson's paper presented in this workshop. Data were taken with a circular nozzle deflected 90 degrees to the ground. The ground board is depicted in Figure 11. Data for the comparison was obtained utilizing time sensitive pressure transducers located along the nozzle path. Reduction of the data to ground board pressures as a function of nozzle path resulted in the pressure profiles shown in Figures 12 to 16. Comparison of the vortex from the moving model with the fixed model data from Reference 5 are shown in Figures 14 and 15. These results show that the vortex from the moving model does not extent as far forward as that from the fixed model tests, Reference 5. Also, as can be seen in Figure 17, the negative pressures under the vortex of the moving jet is greater than either that of Reference 5 or 1. The nozzle pressure ratio for the moving jet was approximately the same as that of Reference 5 so the difference in vortex characteristics would appear to be the effect of the moving vs. the fixed jet, that is the ground board boundary layer. The boundary layer does, most likely, account for the reduced penetration of the vortex into the free stream. The increase in the negative pressure does not appear to be related to the ground boundary layer but is thought to be more accurately relatable to the energy in the wall jet or to the thrust coefficient of the wall jet and to the forward extent of the vortex. This relationship, if true, would indicate that regardless of the penetration of the vortex with different ground boundary layer conditions, the lift loss will be nearly the same at the same jet conditions of angle and thrust coefficients and therefore the aerodynamic effects may be relatable to thrust coefficient. This relationship is likely to be true if the vortex is trapped under the configuration but the suckdown will be configuration dependent when related to the wings and control surfaces on most real configurations. Figure 18 presents the comparison of this moving model data with that of References 1 through 7. This moving model data appears to agree well with that of Abbott, Reference 2, and to be approximately 30 percent less than that from the fixed model and ground board tests. A possible result of the reduced penetration of the ground vortex may be an increase in the pitching moment of the system. A pitch up and a lift loss will result if a vortex is formed by an aft located nozzle such as a thrust reverser. If the lift loss in the actual airplane case, with no ground boundary layer, is the same as the fixed model tests the load center will move aft and the pitch up will be greater for the moving condition.

A second interesting variation of the ground board pressures is also seen in Figures 12 through 16. This data represents one of the few attempts to measure the dynamic characteristics of the ground vortex. As the velocity ratio of the jet, free stream velocity to jet velocity, is reduced the vortex appears to become increasingly less stable. This unsteadiness has been noted in several other studies.

Slot Nozzles and Jet Flaps: Several studies have investigated the effects of slot nozzles in near proximity to the ground. References 5 through 7 discussed one test of a slot nozzle in which the ground vortex was measured. Reference 8 presented a summary of a propulsive wing study for NASA which was later published in Reference 9. This study, Reference 9, as well as most early jet flap tests were aerodynamic characteristic tests and did not measure or visualize the ground vortex penetration. An exception is the work of Butler, Guyett, and Moy, Reference 10. Reference 11 presented additional results of this study. Figure 19 from Reference 10 presents photography views of the development of the ground vortex as the jet impingement point is moved forward and the angle of impact increased by the increasing angle of attack of the model. At zero angle of attack the ground vortex is undefined, it may be present outboard and well aft. As the angle of attack is increased the vortex becomes well defined and is located under and eventually ahead of the wing. Figure 20, Reference 10, presents a graphic description of the vortex flow field. The cross section of the flow field shows two vortex patterns, first a large vortex under the wing and secondly a tightly rolled secondary vortex on the ground ahead of the larger vortex.

An early look at the effects of a moving ground belt on the ground effects of a jet flap was done by Butler, Moy, and Hutchins, Reference 12. This study investigated the effect of the moving belt on the aerodynamics and on the ground vortex and flow field under the jet flap wing. Figures 21 and 22 show the effect of the moving belt on the flow field. The flow field was visualized by a series of tufts attached to wires under the wing. In Figure 21 at an angle of attack of 5 degrees the moving belt appears to reduce the forward extent of the vortex. At 15 degrees angle of attack, Figure 22, the effect is less apparent. These data are both at a blowing coefficient of 4.0.

The ground effects of these configurations is seen in Figures 23 and 24. The data for the configuration of Reference 10 seen in Figure 23. The lift coefficient is seen to be unaffected by the ground at low angles of attack and at low blowing coefficients, however, at combinations of blowing coefficients and angle of attack which produce large lift coefficients, the effect of the ground is significant. The large losses in lift coefficient seen on this configuration may be attributed, in effect, to the ground vortex. If the presence of the ground boundary layer affects the vortex it will also effect the lift loss. Figure 24 shows the effect of the moving belt on the lift coefficient of the configuration of Reference 12. The lift coefficient at the higher angle of attack and blowing coefficient is greater with the moving belt.

A similar pattern is shown on the lower surface pressure distribution of a low aspect propulsive wing, Reference 8. These pressure variations, Figure 25, seem to indicate the double vortex discussed earlier. The slot jet of Reference 5 is summarized in References 6 and 8. The ground board pressures and lift losses are presented in Figures 26 and 27. Figure 26 presents pressure and lift data at a jet deflection of 90 degrees and Figure 27 presents the same data for 45 degree deflection. In the latter case, the vortex is formed aft of the wing and a positive incremental lift is seen at near proximity to the ground. The deflection of 90 degrees produces a vortex ahead of the wing and a significant lift loss.

Unpublished data from a later test of the low aspect ratio propulsive wing did not measure the ground vortex, but as can be seen in Figure 28 a large lift loss is experienced at low heights and large blowing coefficients indicate the presence of the ground vortex.

One result of the of the ground vortex of the jet flap configurations is the requirement for a moving ground belt for near ground testing. Turner, Reference 13, established a boundary of height and lift coefficient for moving belt testing. The results of the vortex effects of References 5, 9, and 13 indicate that the requirement for the belt may be more critical than that established by Turner. Turner's data was for relatively large aspect ratio wings. The later data is for lower aspect ratios and appear to suggest that the region requiring a moving belt should be expanded. Figure 29 compares the limits set by Turner and that indicated by the ground vortex and propulsive wing tests. These data were established with a fixed ground board. There is not sufficient data to determine what, if any, effect the moving belt would have on the vortex formation or the aerodynamic characteristics of these configurations.

CONCLUSIONS

The presence of a ground vortex due to the interaction of the wall jet and the free stream is well established.

The vortex affects the aerodynamic characteristics of the airplane. A lift loss due to the negative pressures in the vortex is generally experienced. If the jet producing the vortex is well aft on the configuration, a pitch up will also be experienced.

The effect of the boundary layer on the ground ahead of the configuration appears to be significant in the development of the vortex. Approximately a thirty percent reduction in the vortex penetration is indicated when the boundary layer is eliminated.

The presence of the ground vortex and the significant effect of that vortex on the aerodynamic characteristics indicate that a moving ground board should be considered for all STOL powered model ground effects testing. A moving model technique may be preferred if the data gathering capabilities are not too restrictive.

RECOMMENDATIONS

The ground vortex characteristics need further definition. Testing should be accomplished to compare fixed and moving ground boards and to compare both with the moving model technique. These tests are needed for both concentrated jets and for slot nozzles, jet flaps.

The dynamics of the vortex should be investigated. The single piece of quantitative dynamic data available indicates that the vortex unsteadiness is a function of the forward speed.

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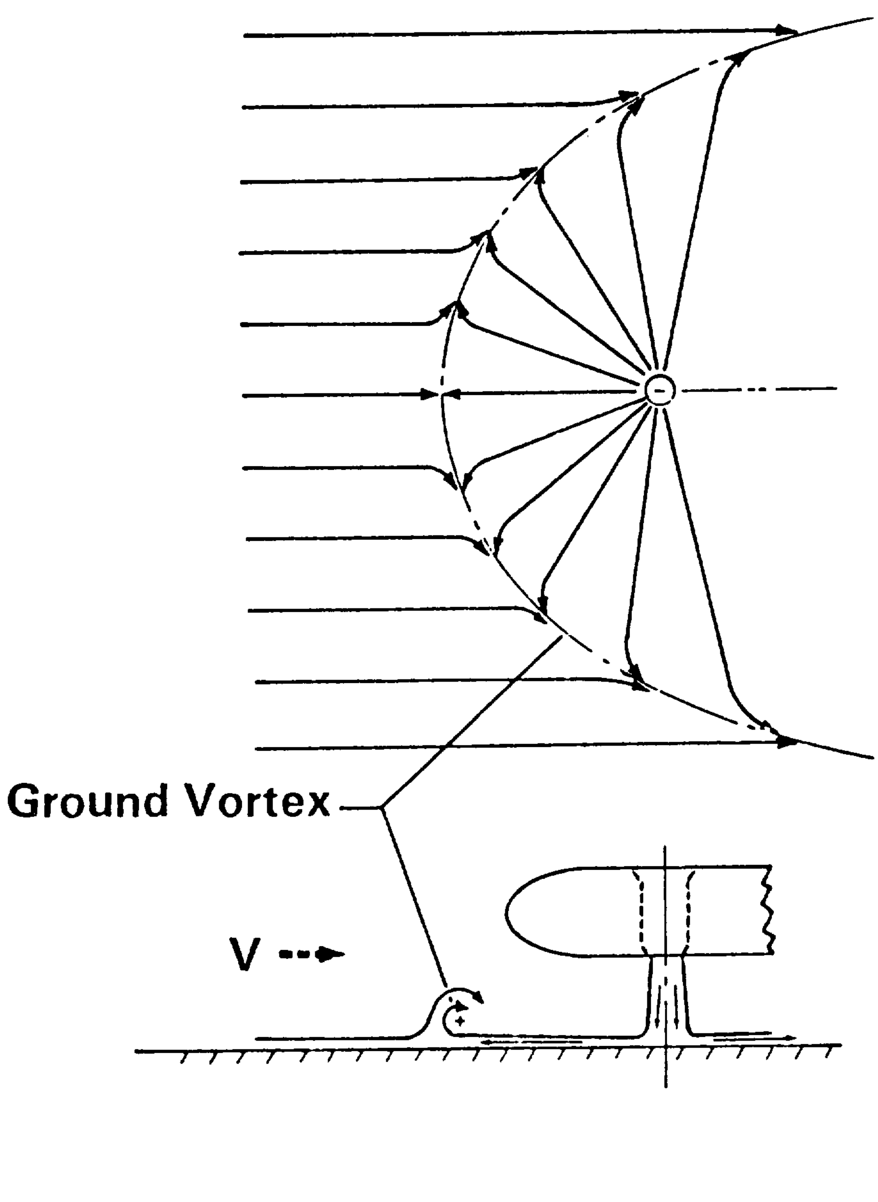


Figure 1. Formation of the Ground Vortex

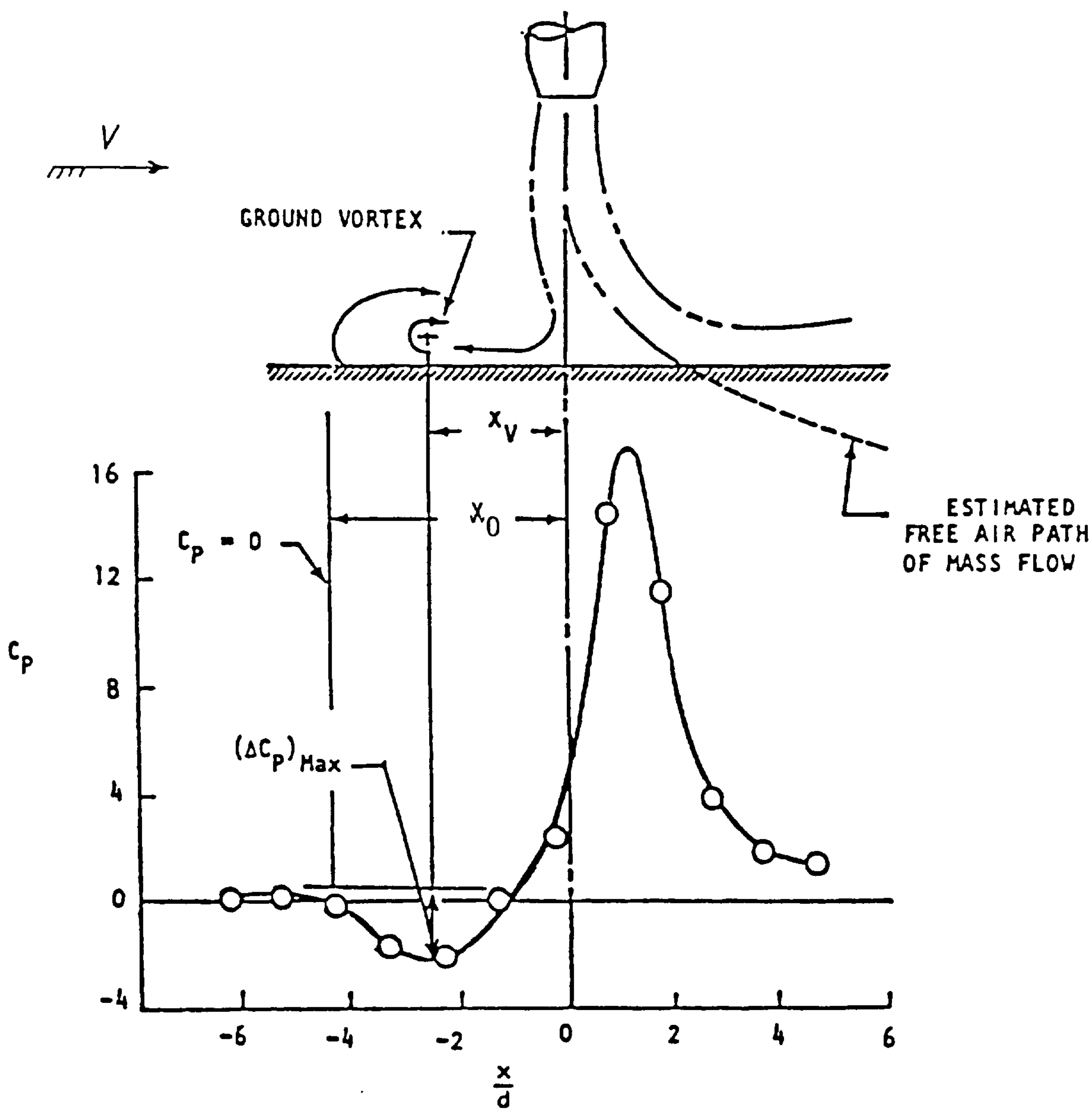


Figure 2. Typical Pressure Distribution and Definition of Terms

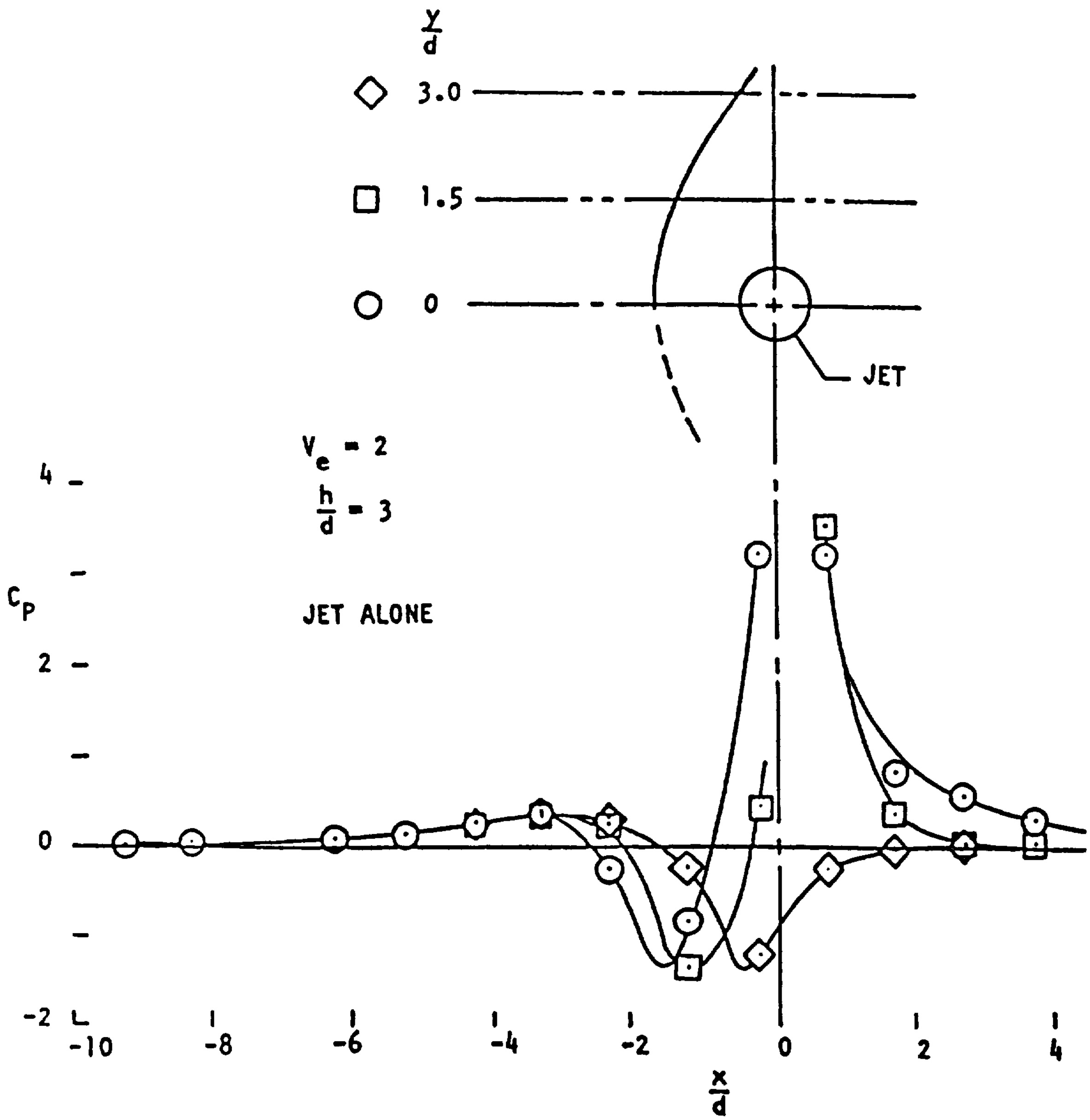


Figure 3. Ground Board Pressures Due to Jet and Vortex

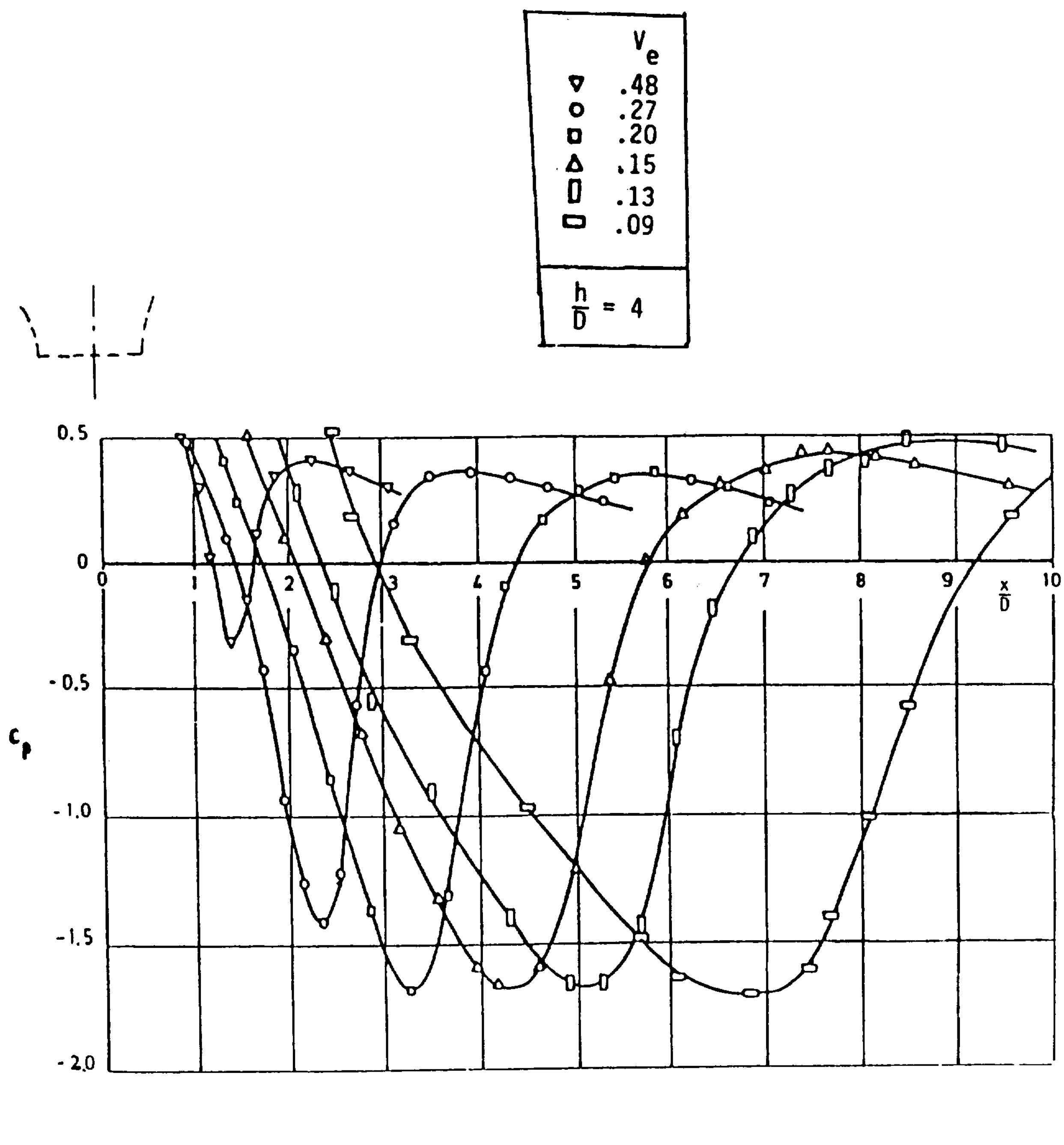


Figure 4. Wall Static Pressure Distribution (Ref.1)

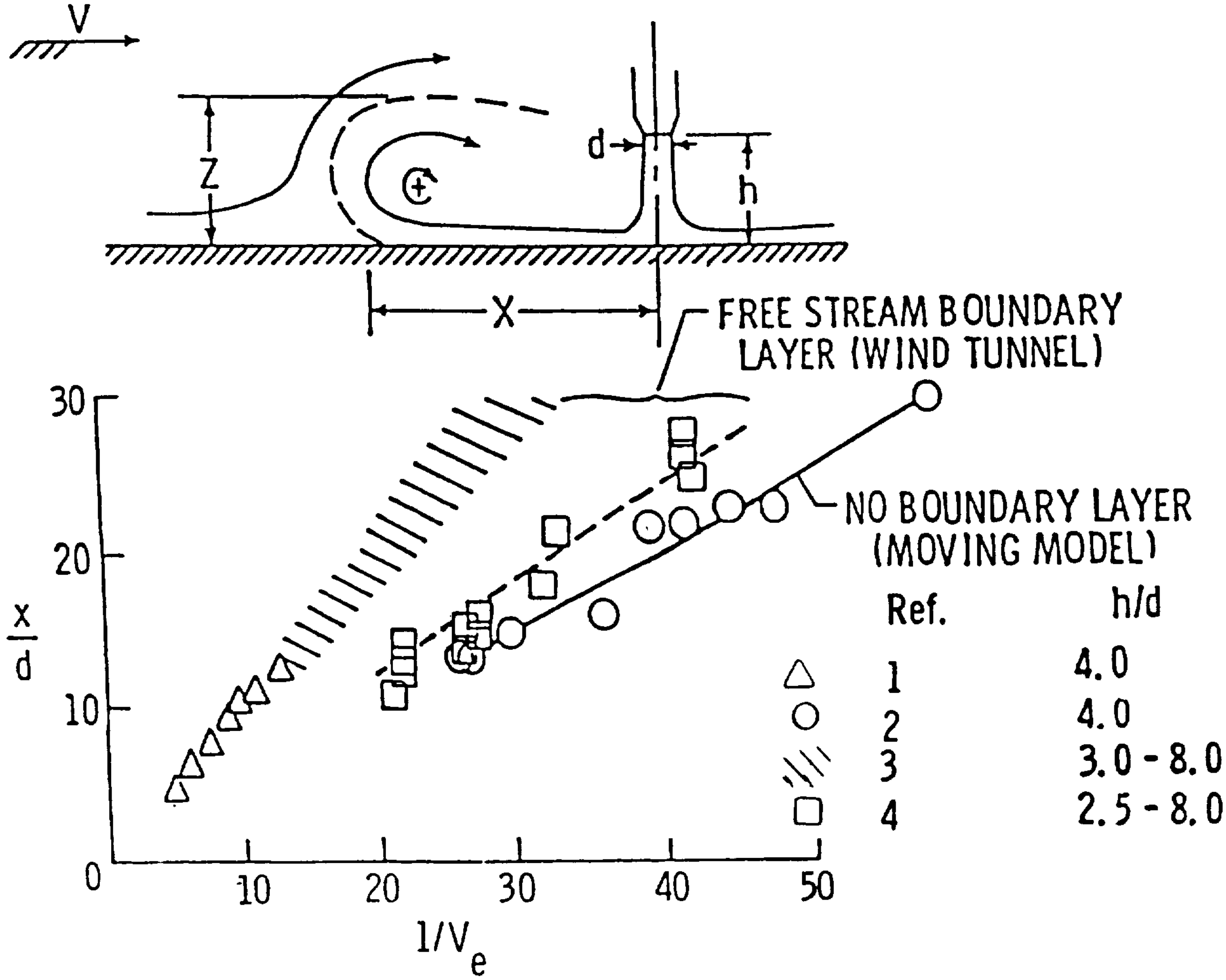


Figure 5. Forward Extent of Ground Vortex

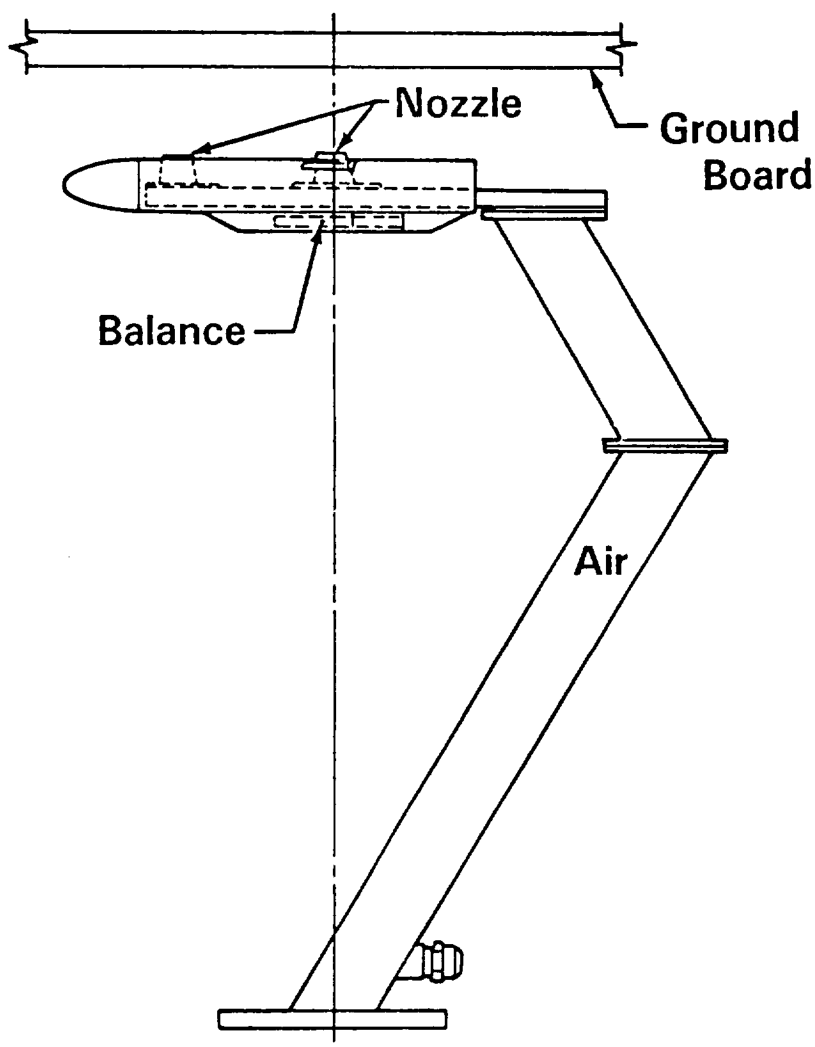


Figure 6. Model Installation

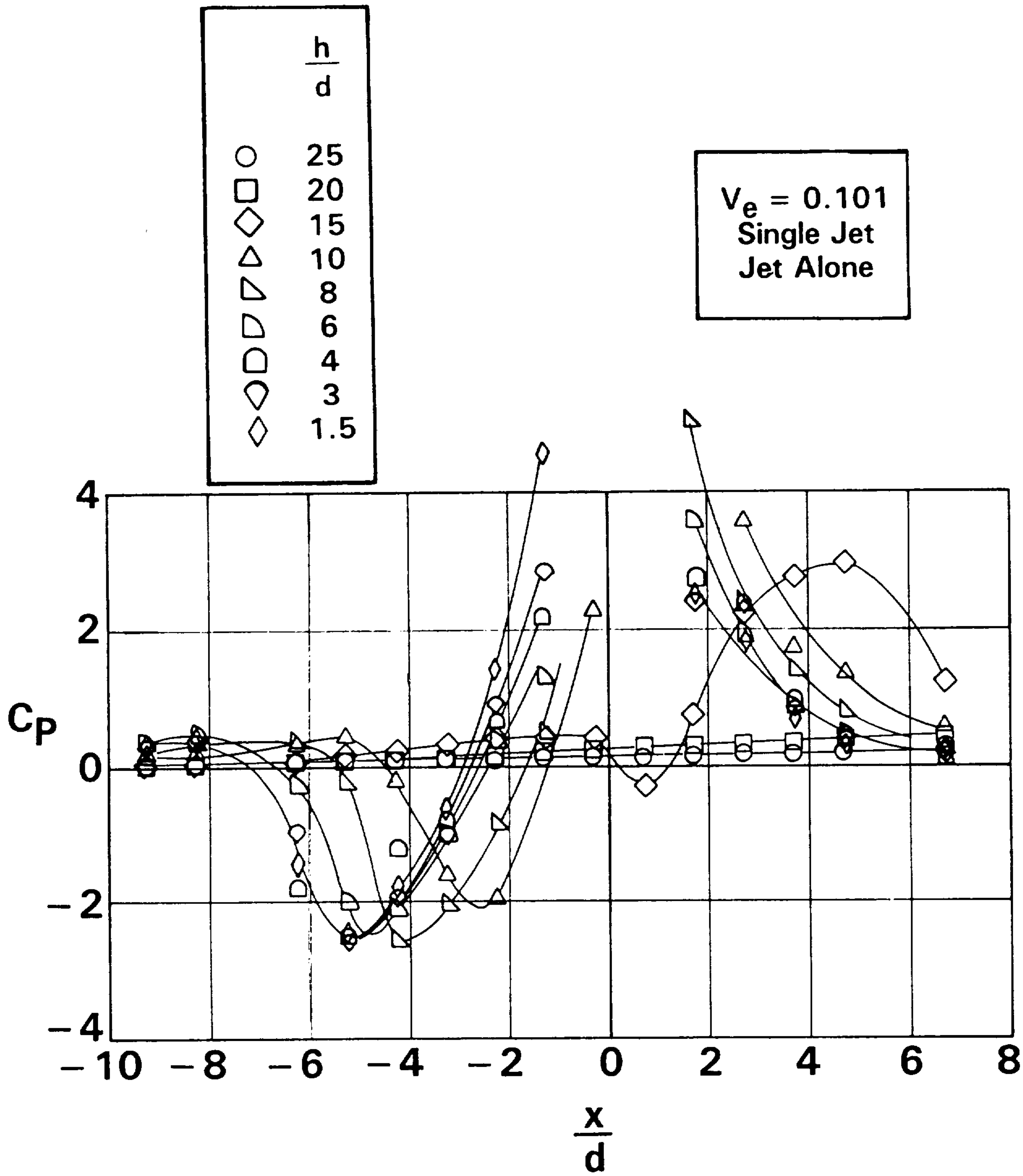


Figure 7. Effect of Height on Pressure Distribution Measured on Ground Board

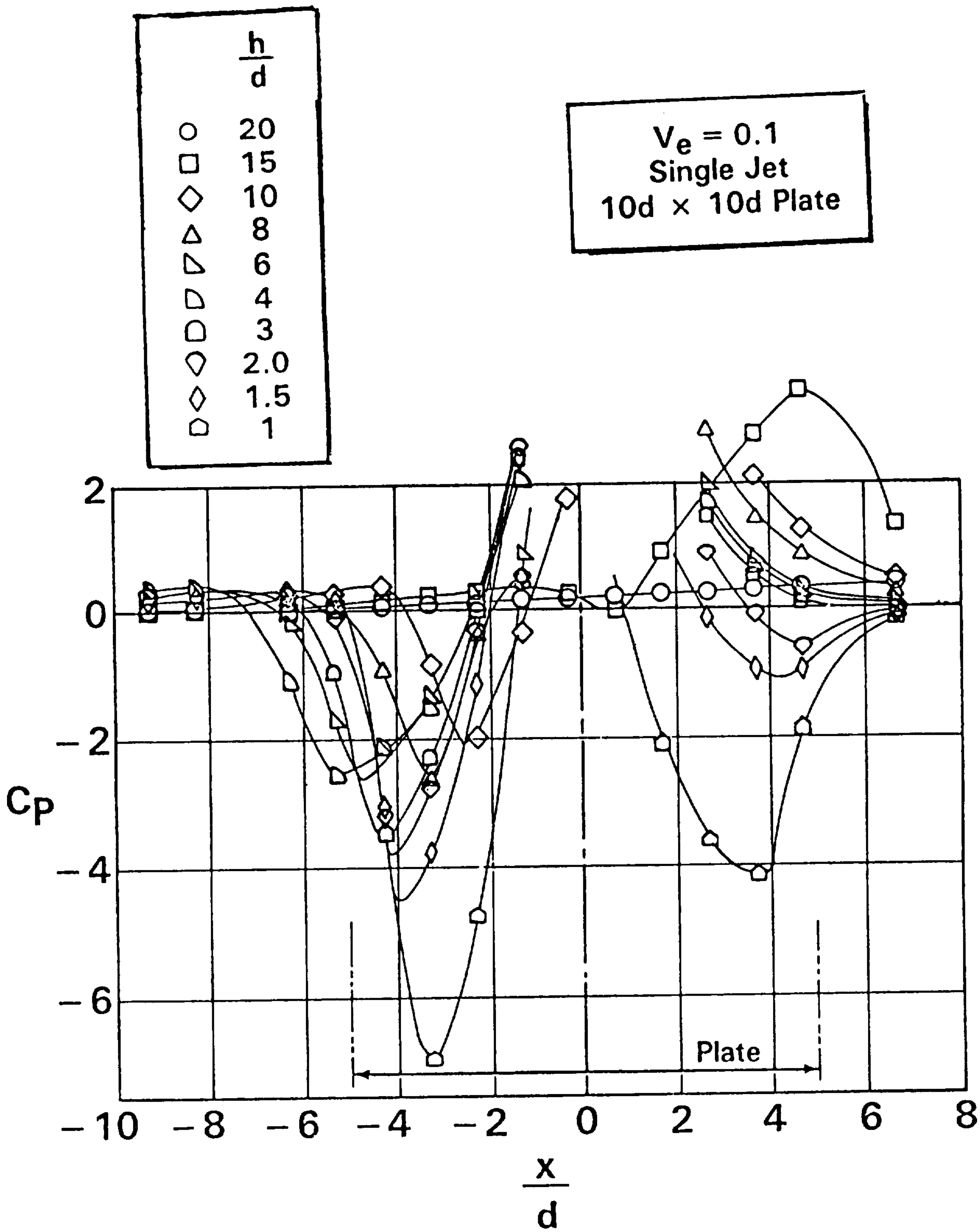


Figure 8. Effect of Height with Large Plate on Ground Board Pressures

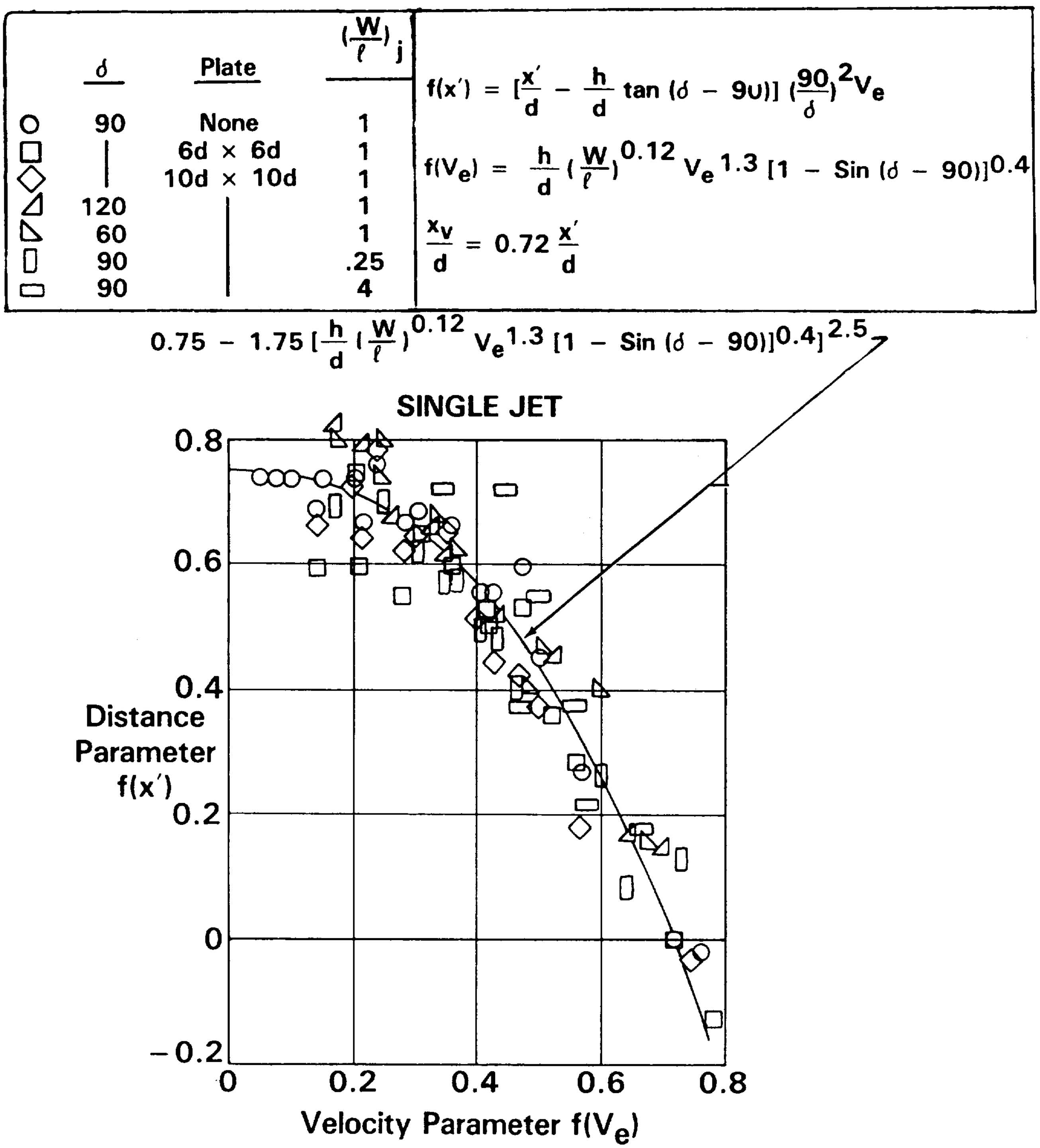


Figure 9. Correlation of Forward Extent of Vortex

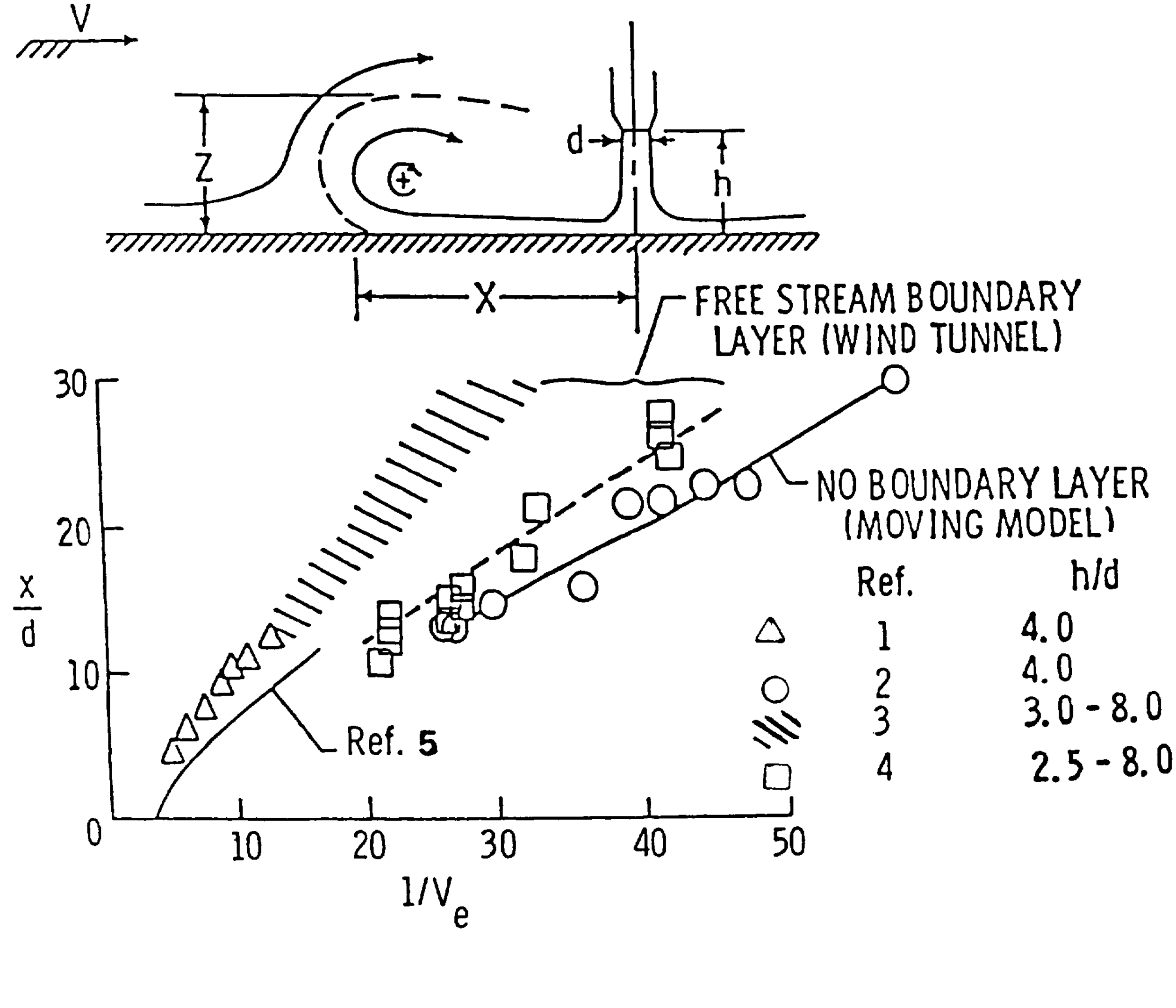


Figure 10. Forward Extent of Ground Vortex

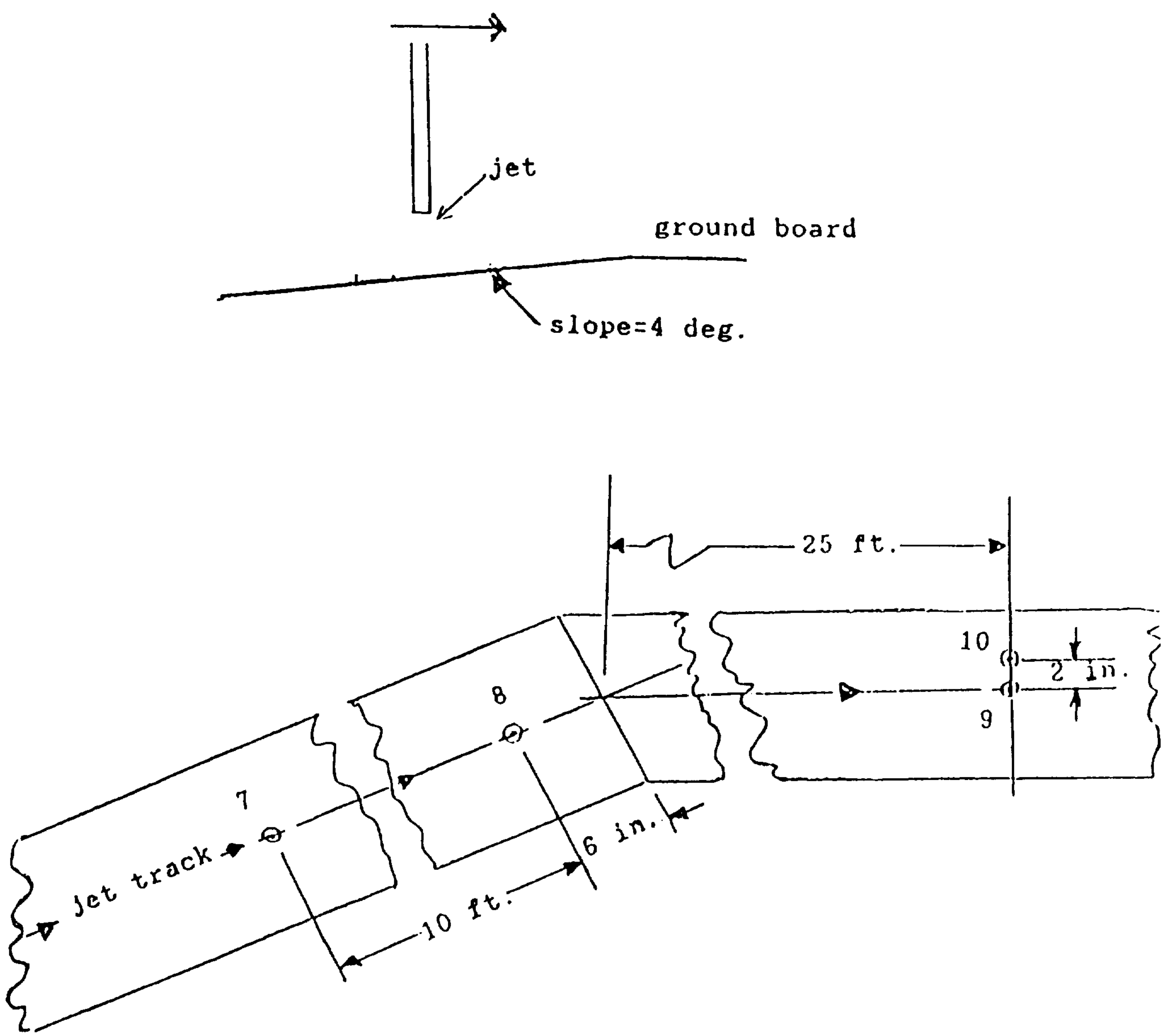


Figure 11. Moving Model Ground Board Instrumentation

TRANSDUCER # 9, Ve=.080, h/d=3.0,

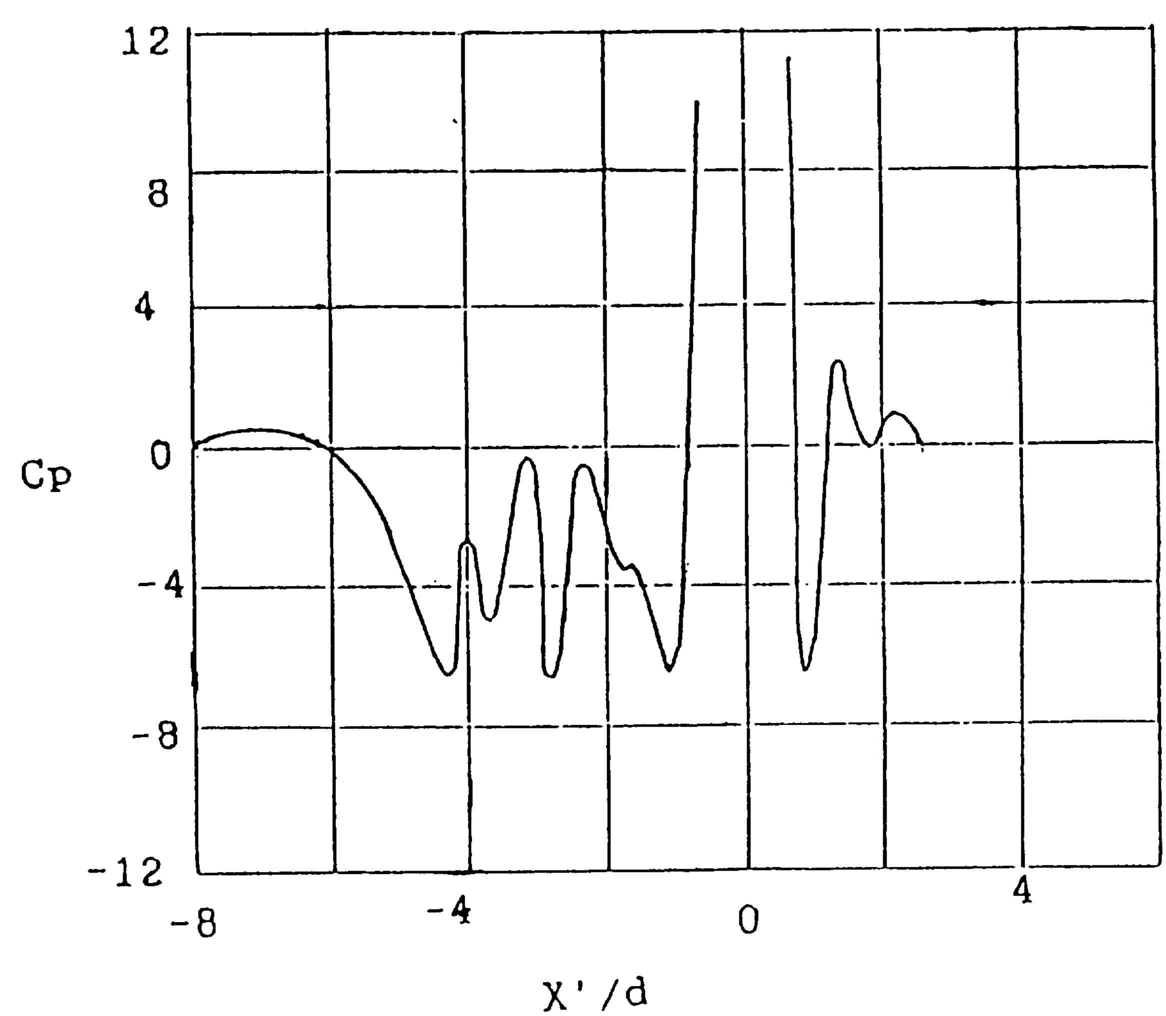


Figure 12. Moving Model Ground Board Pressures

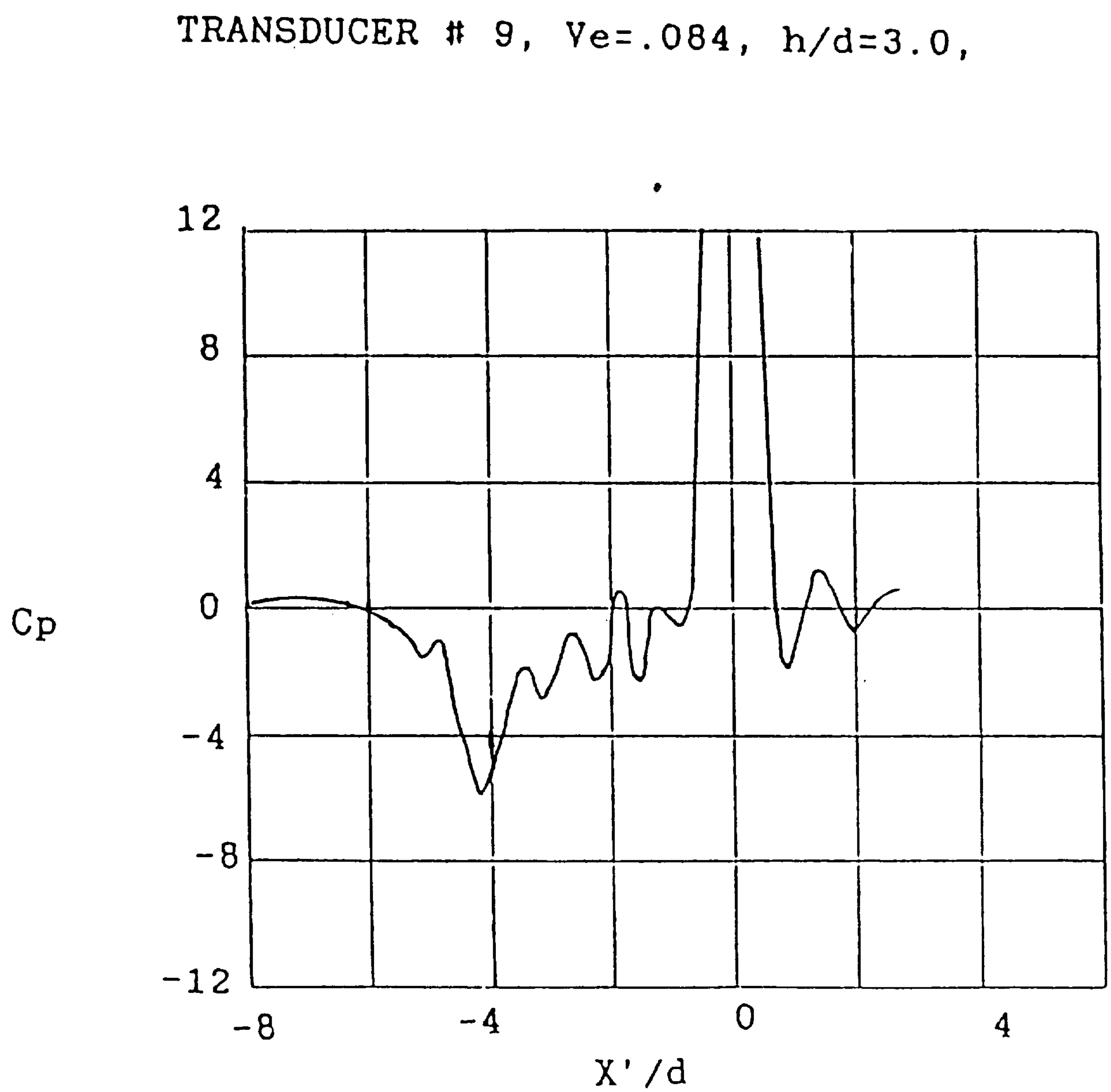


Figure 13. Moving Model Ground Board Pressures

TRANSDUCER # 9, Ve=.093, h/d=3.0

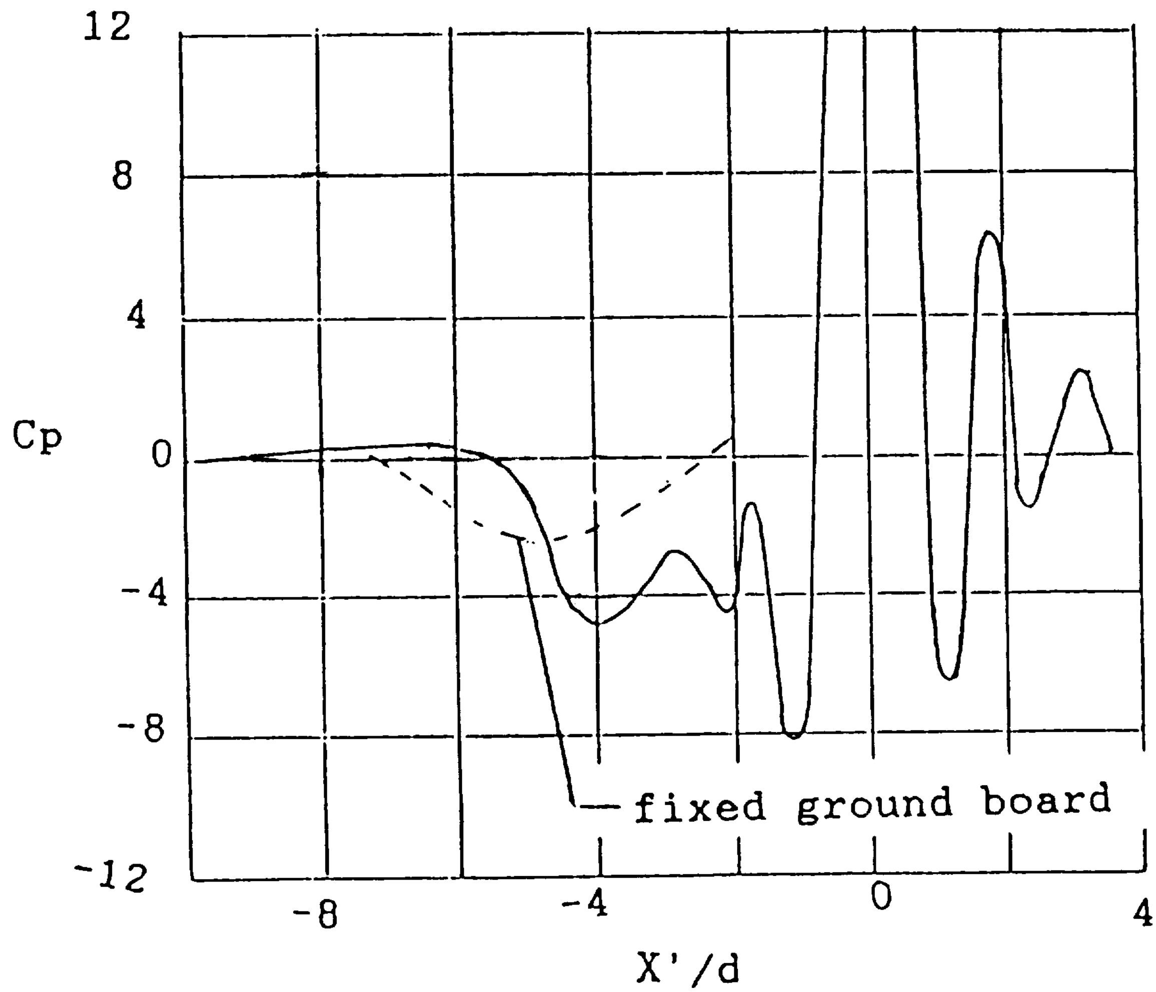


Figure 14. Moving Model Ground Board Pressures

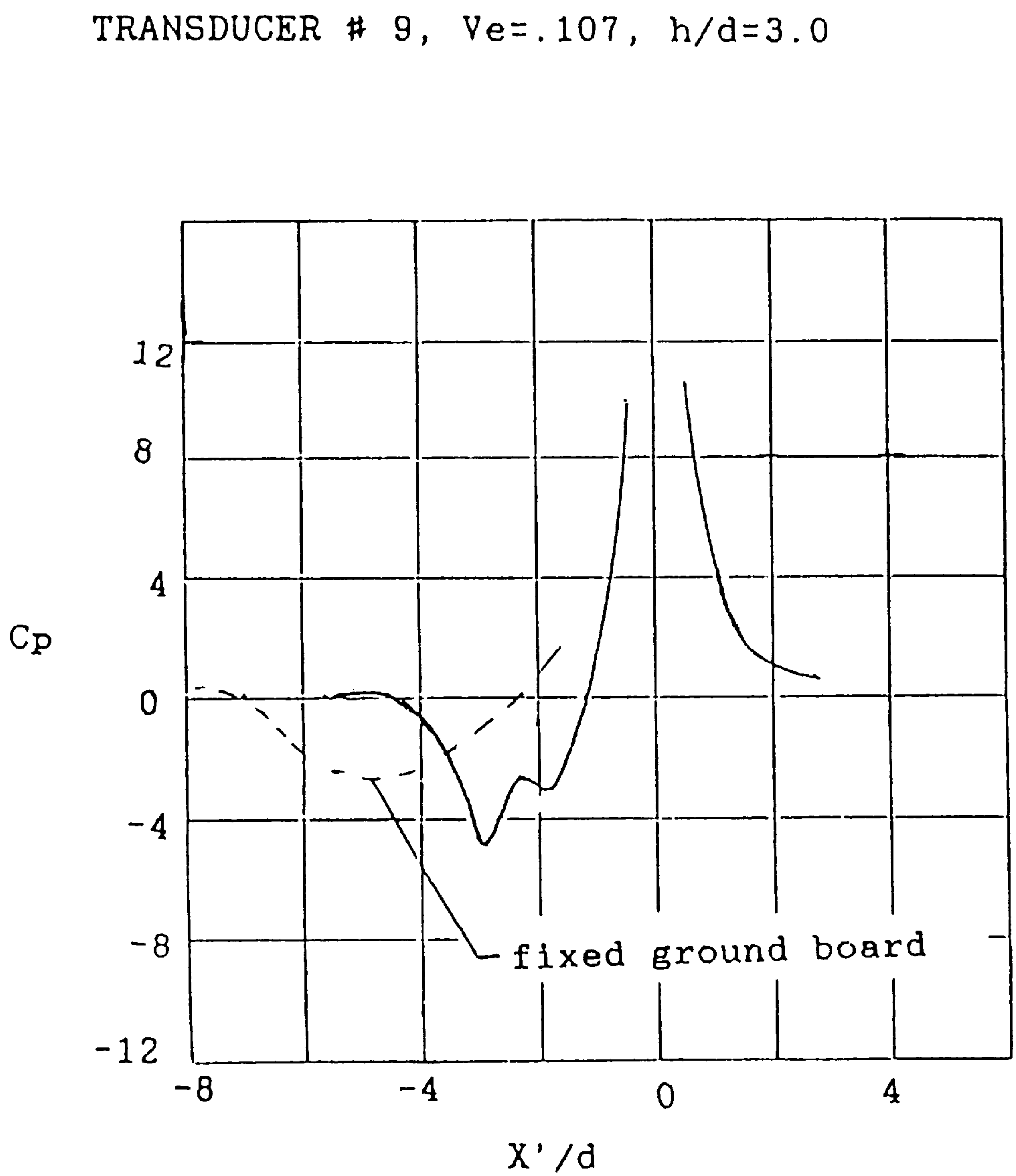


Figure 15. Moving Model Ground Board Pressures

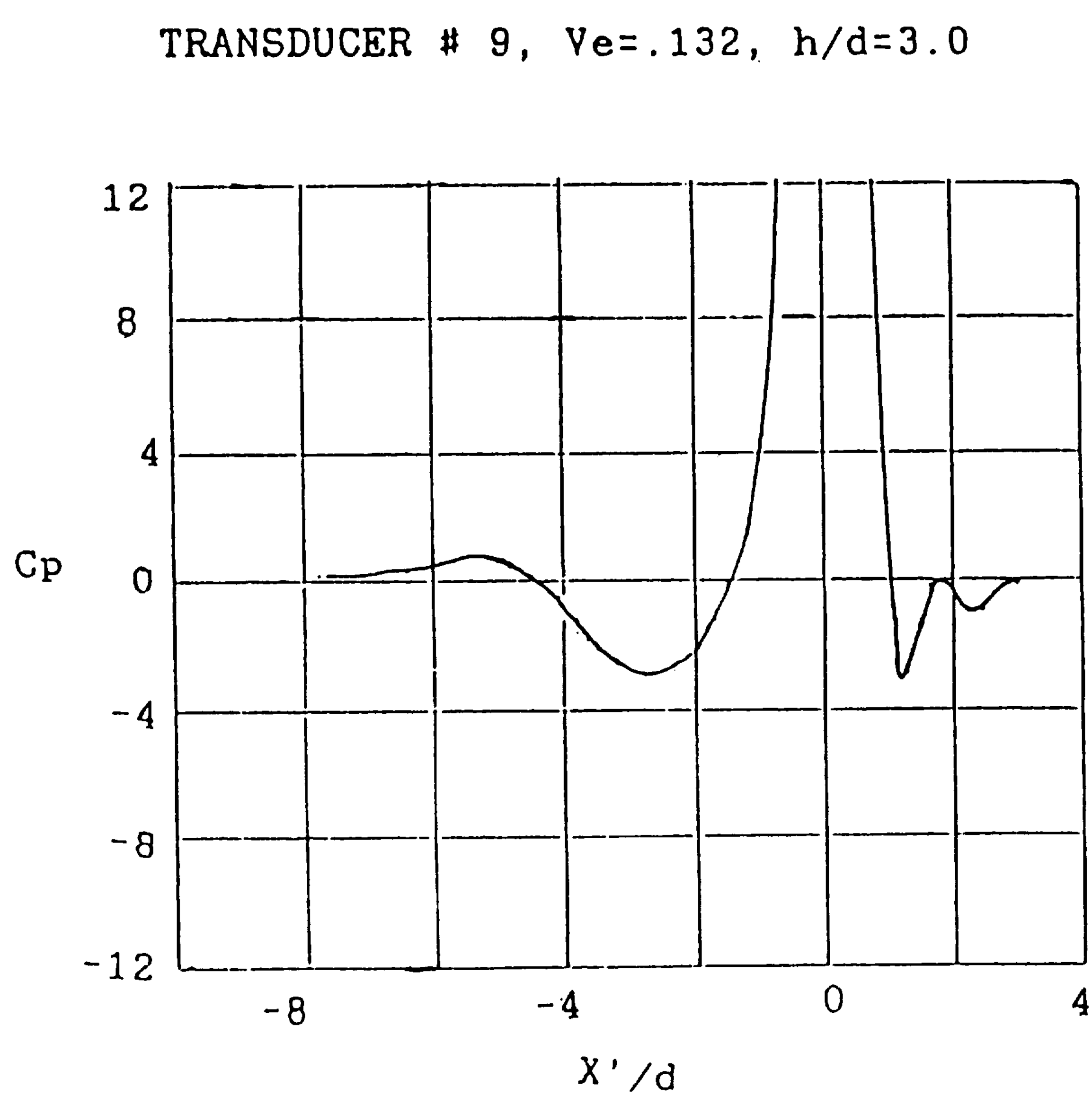


Figure 16. Moving Model Ground Board Pressures

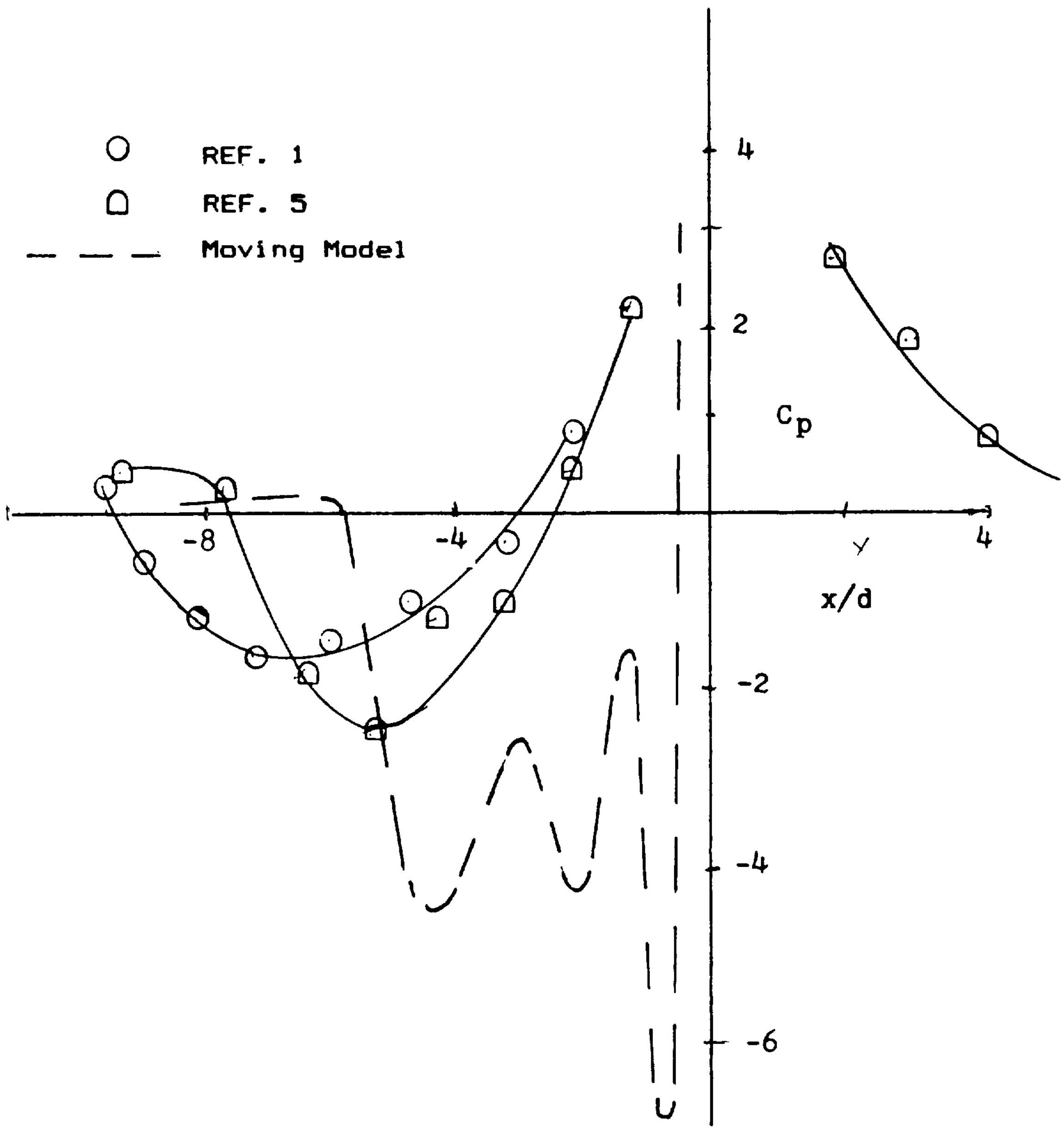


Figure 17. Comparison of Ground Vortex

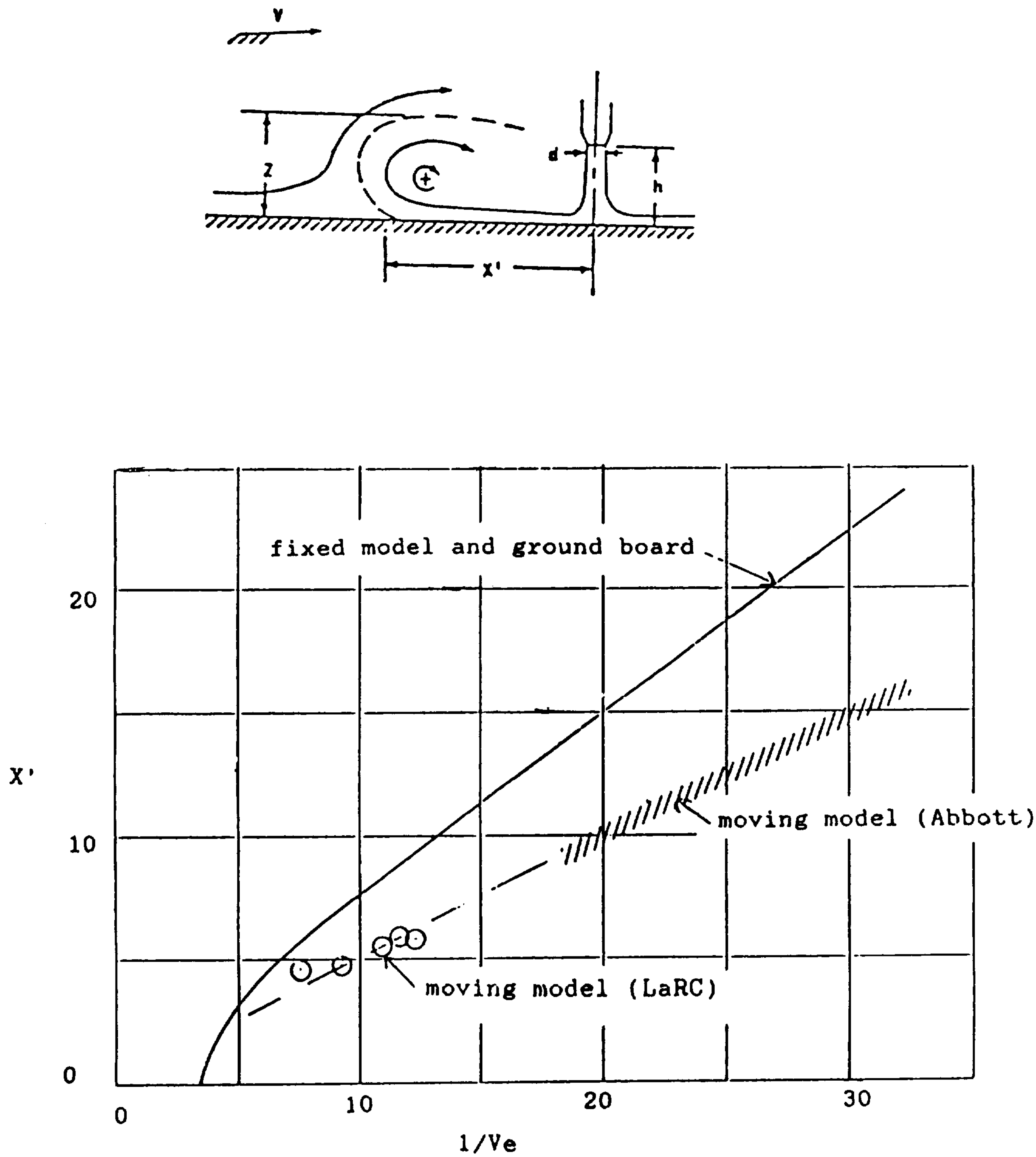
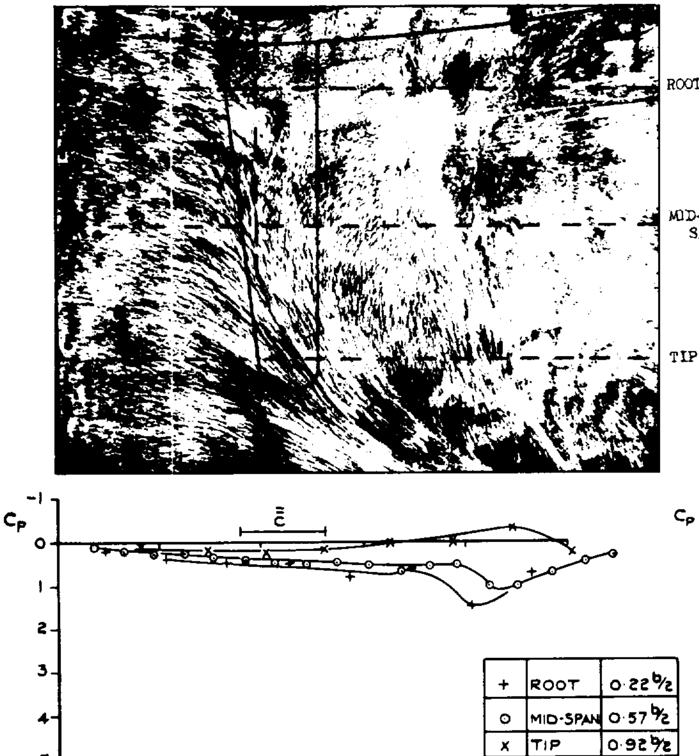
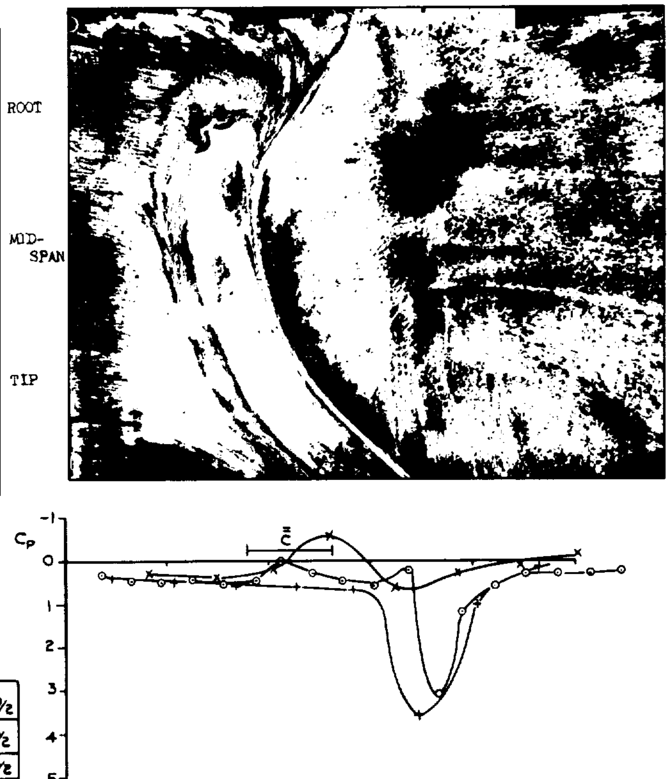


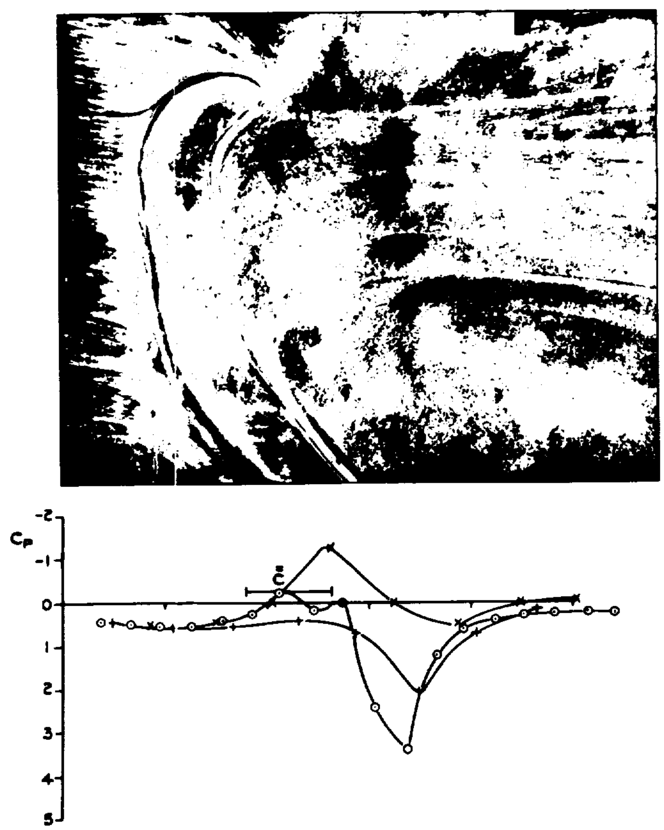
Figure 18. Effect of Moving Model of the Penetration of the Ground Vortex



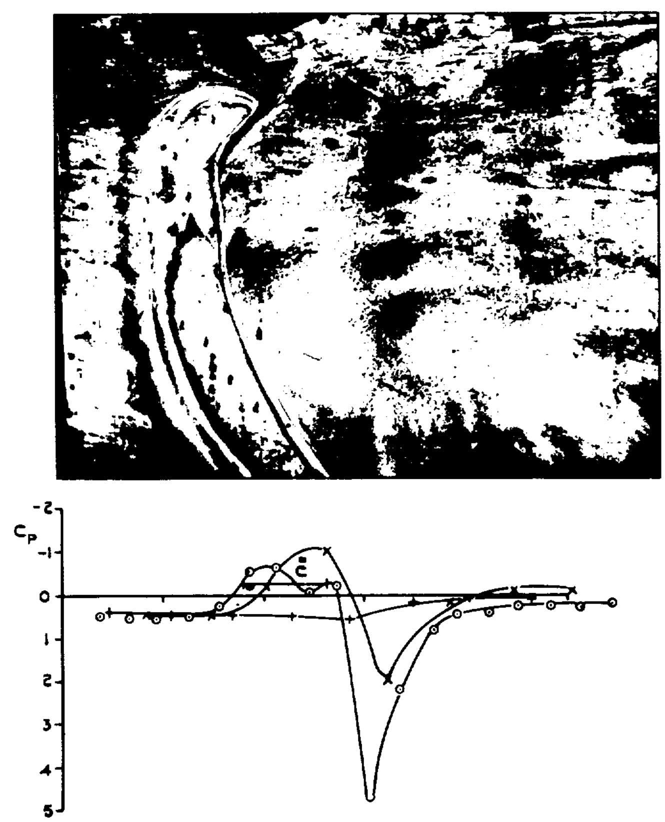
(a) $\alpha_w = 0^o$



(b) $\alpha_w = 10^o$



(c) $\alpha_w = 15^o$



(d) $\alpha_w = 17.5^o$

Figure 19. Ground Board Flow Patterns and Pressure Distributions

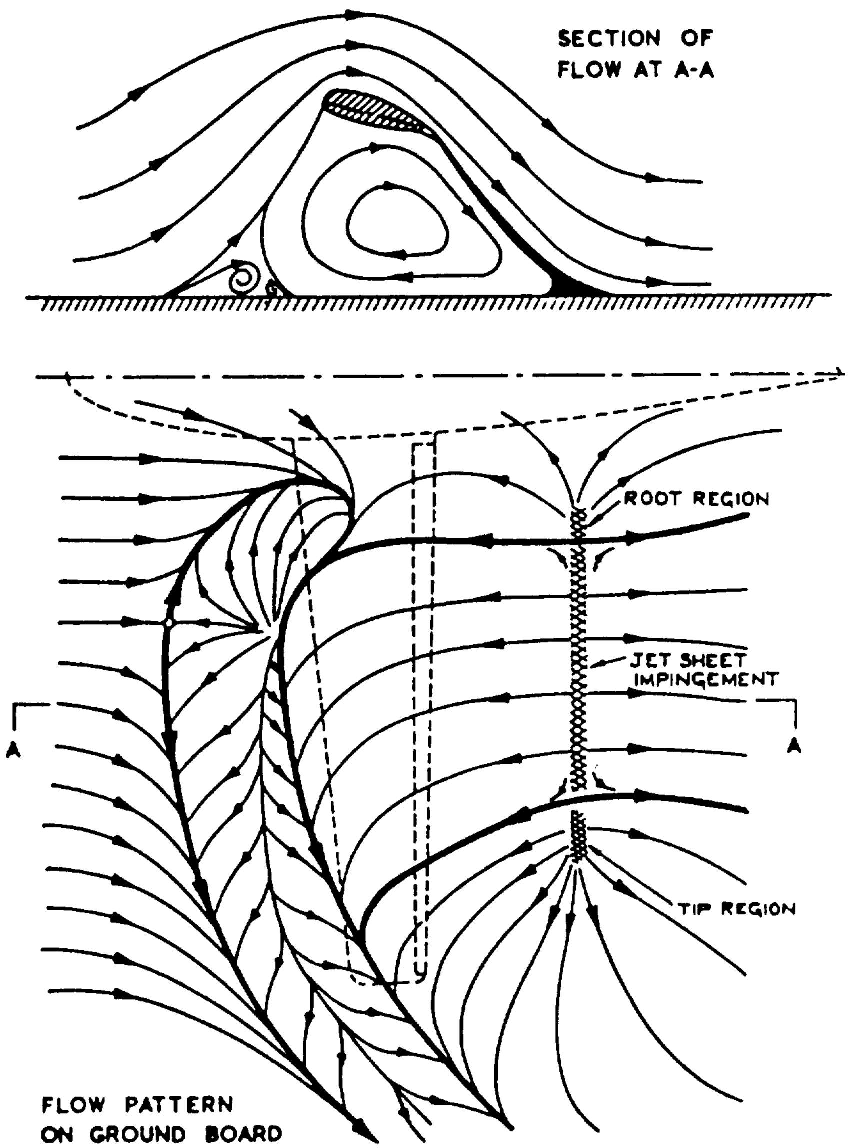


Figure 20. Jet Flap Flow (Ref. 10)

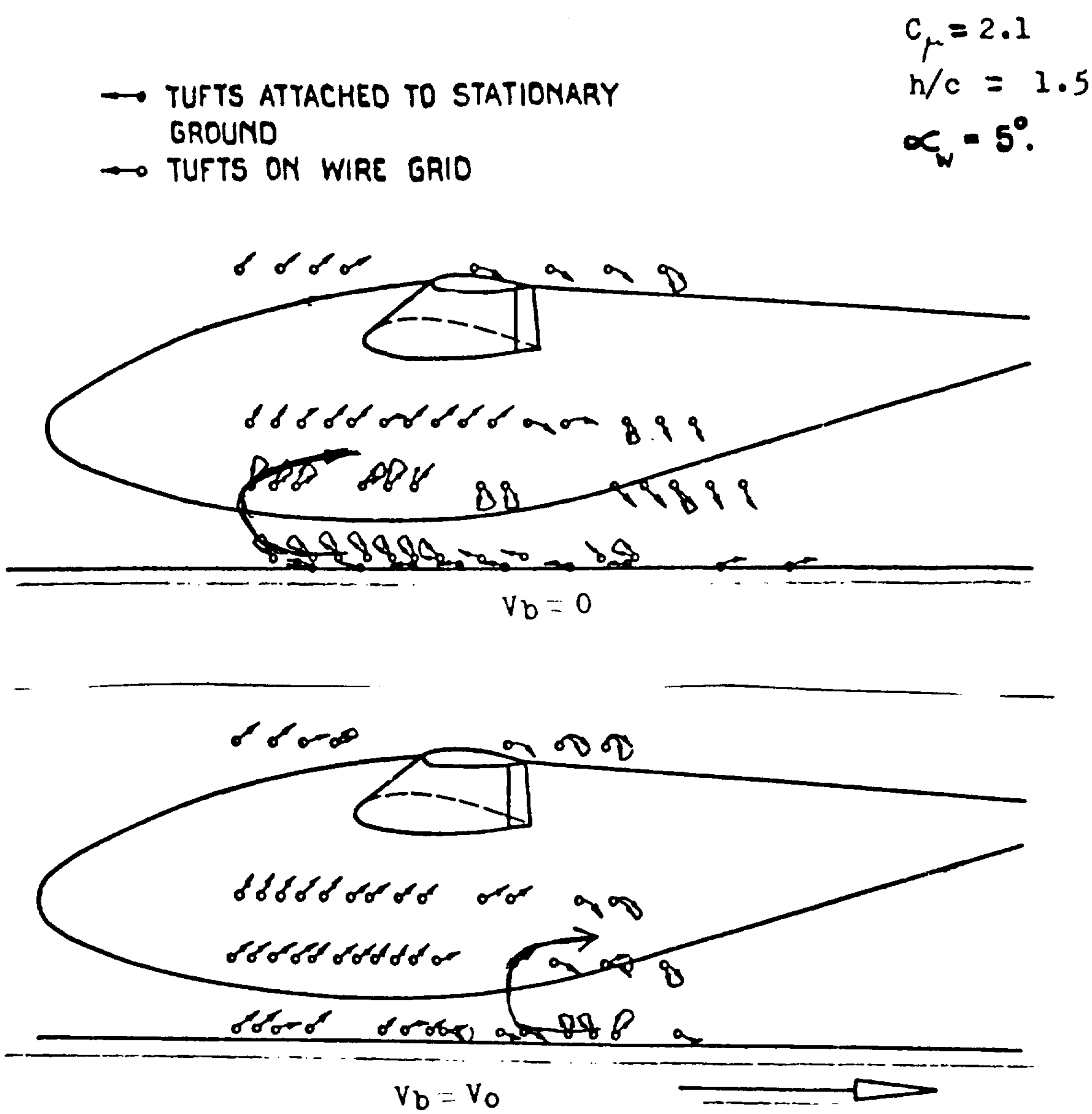


Figure 21. Effect of Moving Belt on Ground Vortex

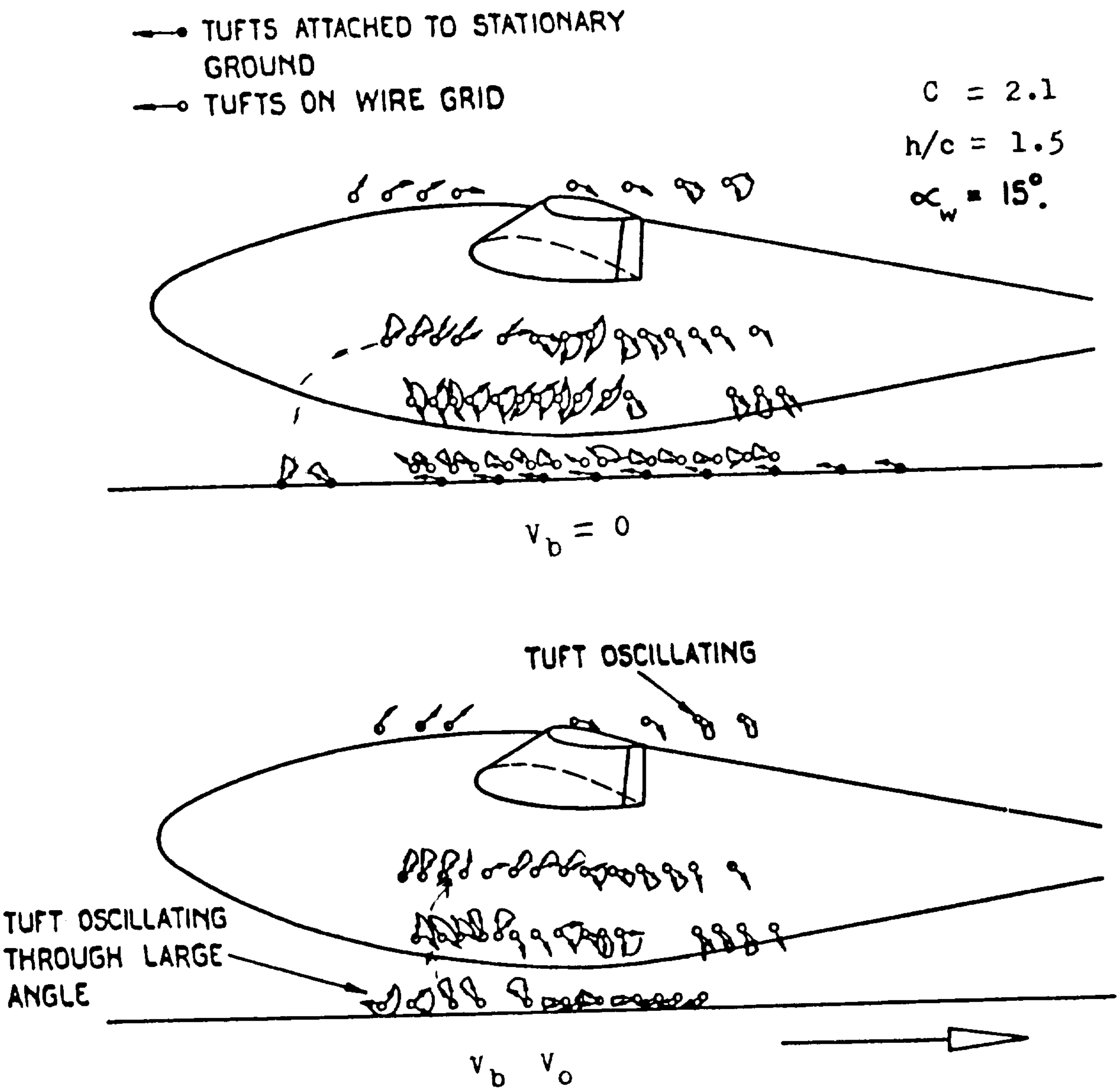
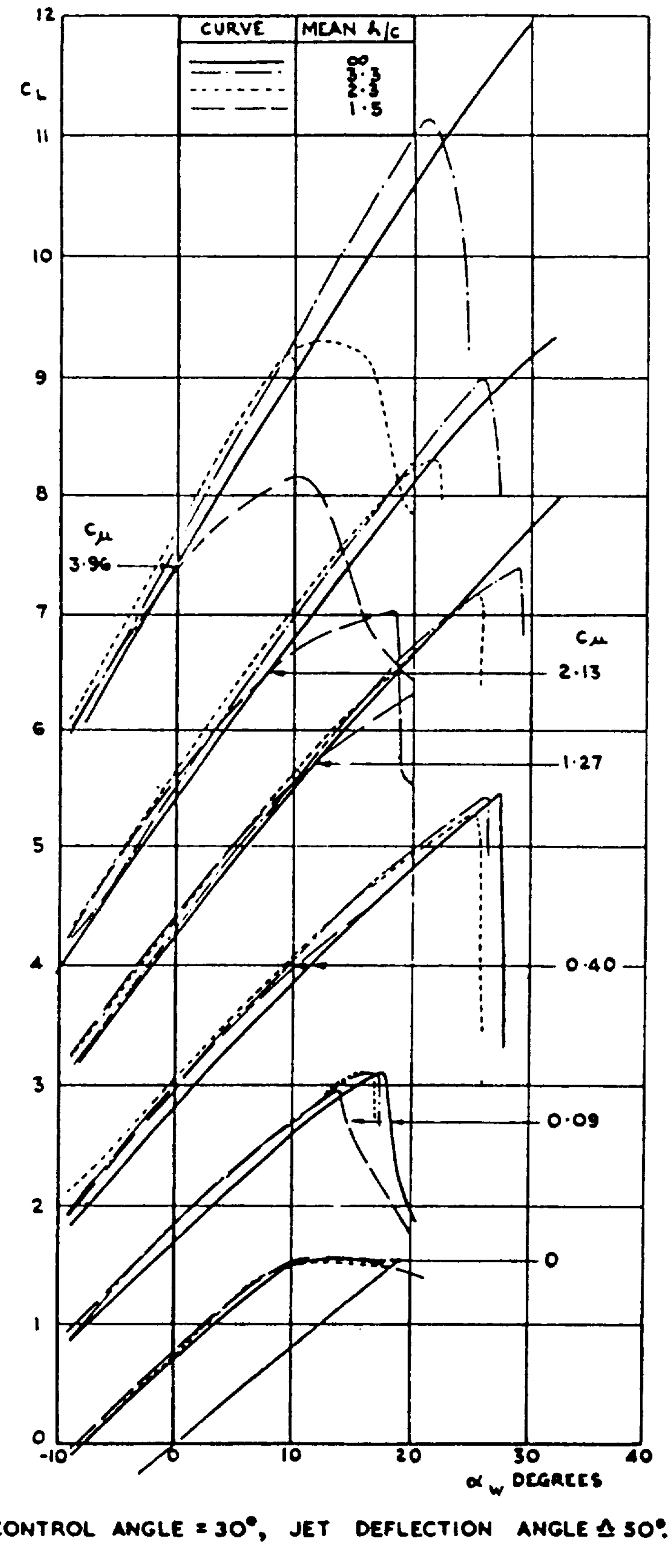


Figure 22. Effect of Moving Belt on Ground Vortex



CONTROL ANGLE = 30°, JET DEFLECTION ANGLE ≙ 50°.

Figure 23. Effect of Ground Vortex on Lift Coefficient (Ref 10)

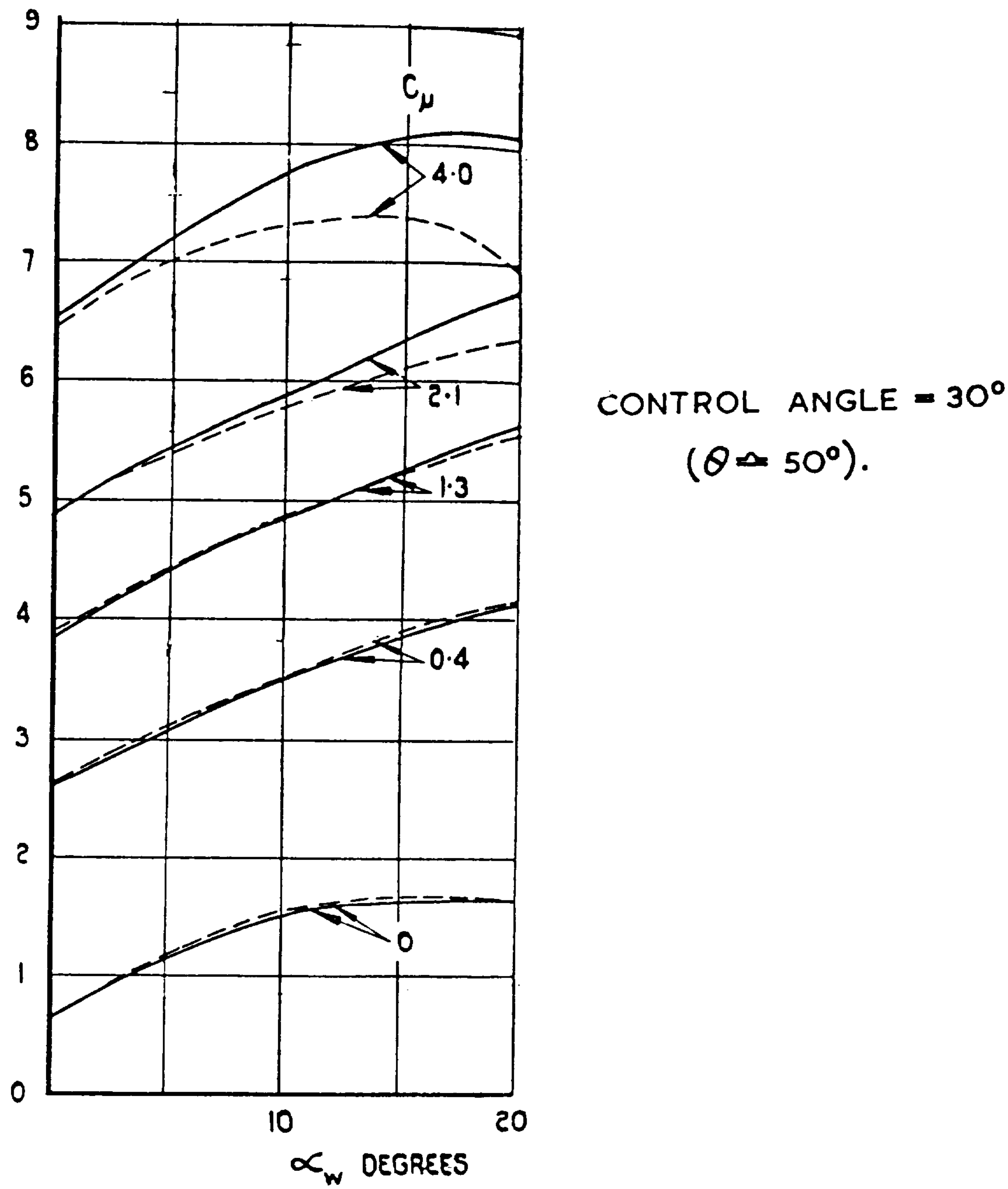


Figure 24. Effect of Moving Belt on Lift Coefficient (Ref 11)

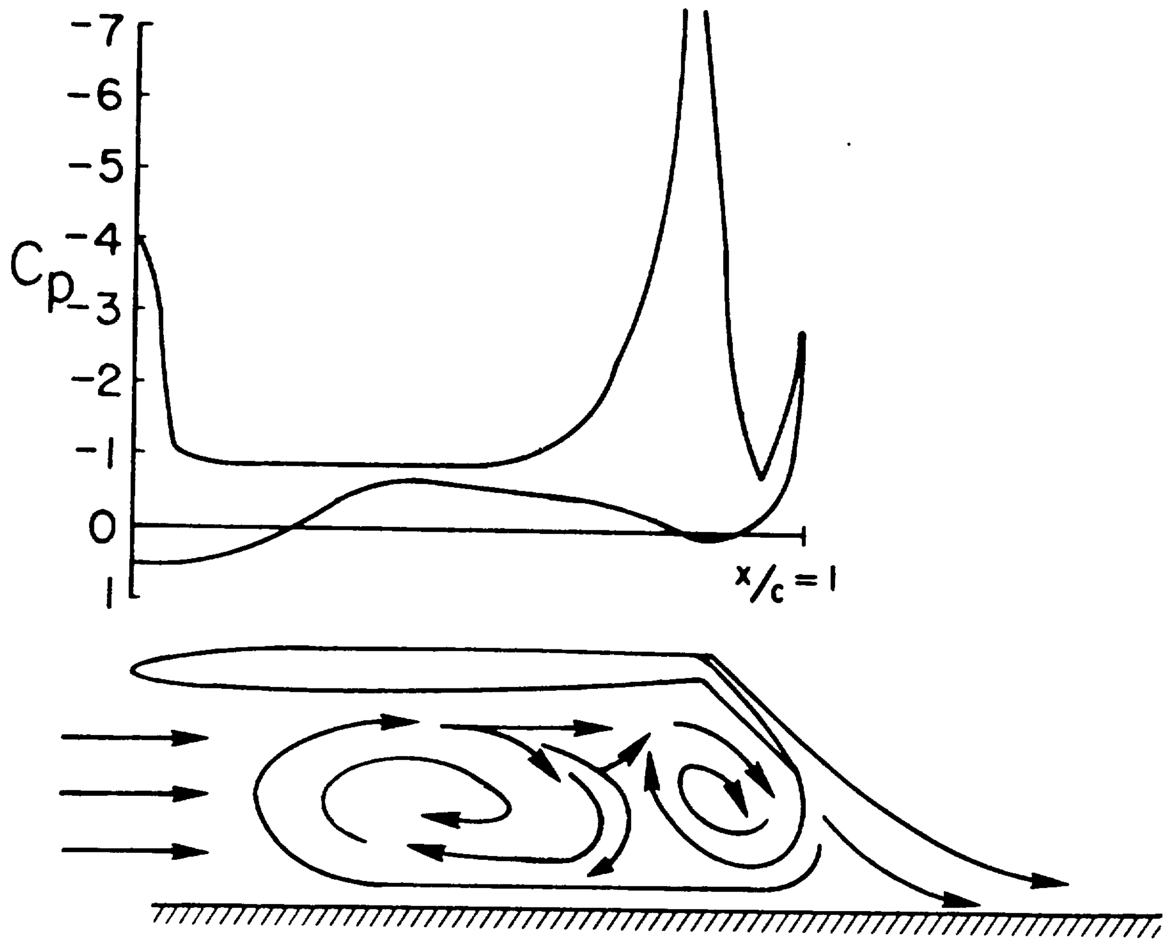


Figure 25. Pressure Distribution on a Wing with a Jet Flap

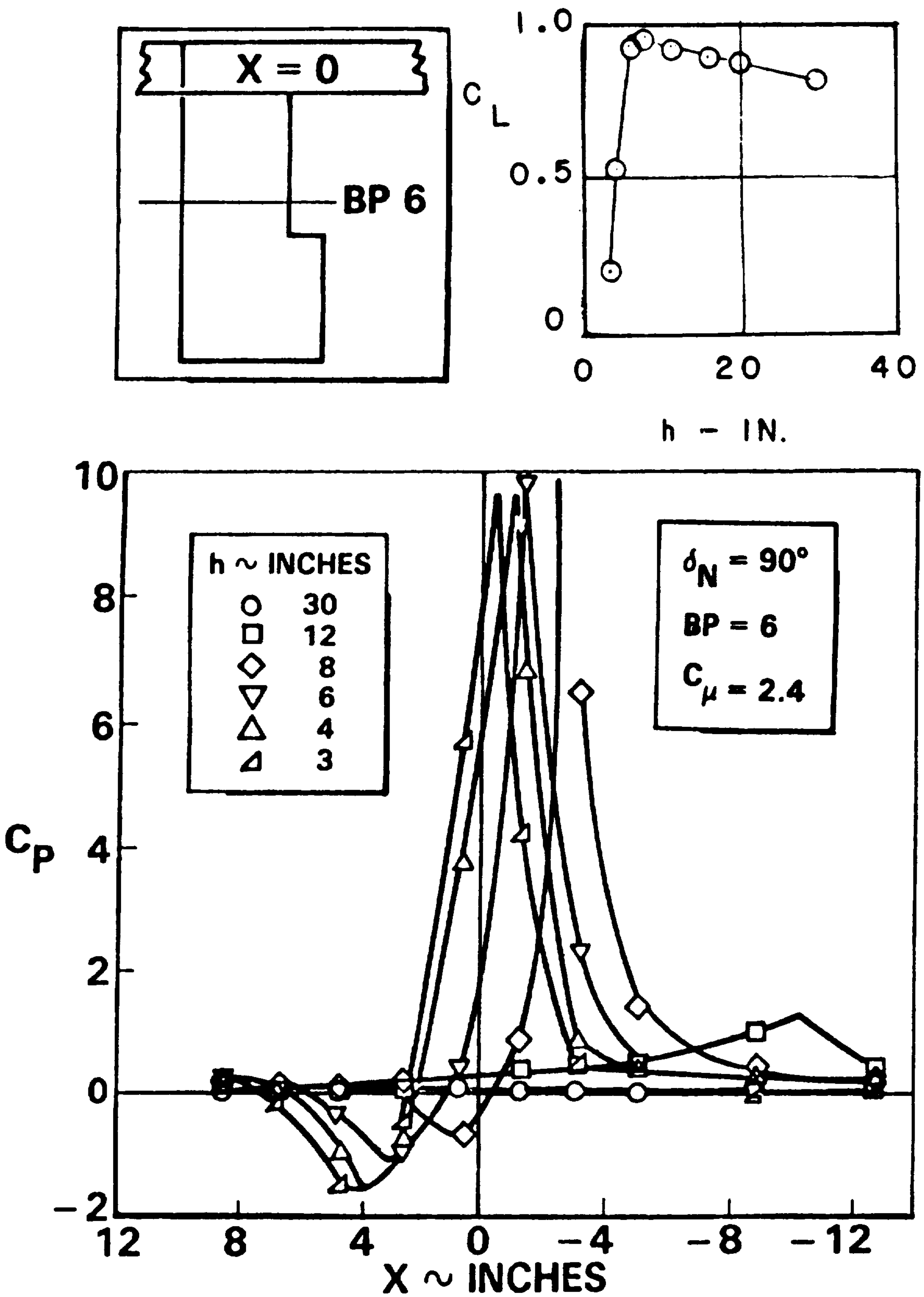


Figure 26. Ground Board Pressure Distribution, Jet Flap

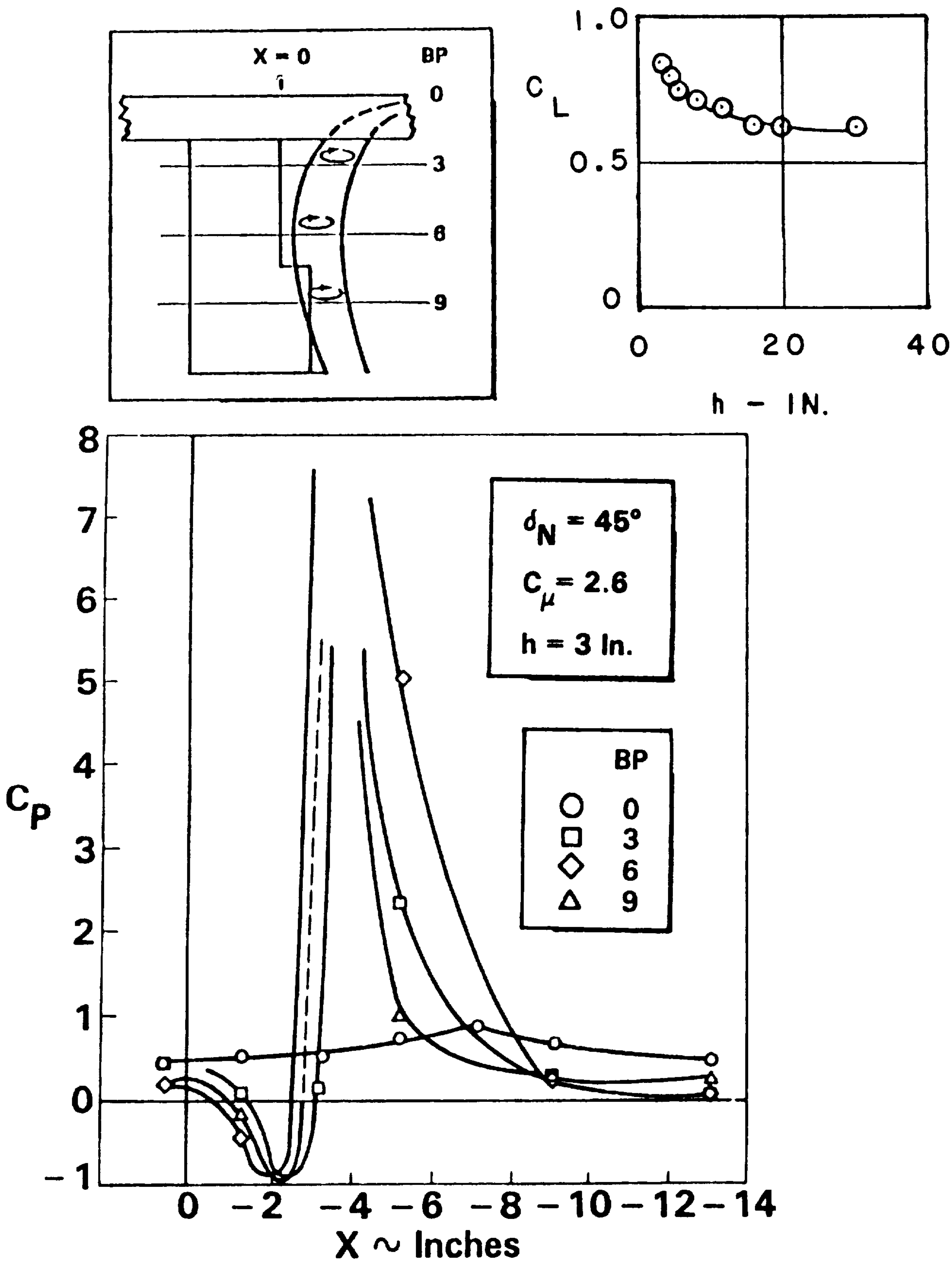


Figure 27. Ground Board Pressure Distribution, Jet Flap

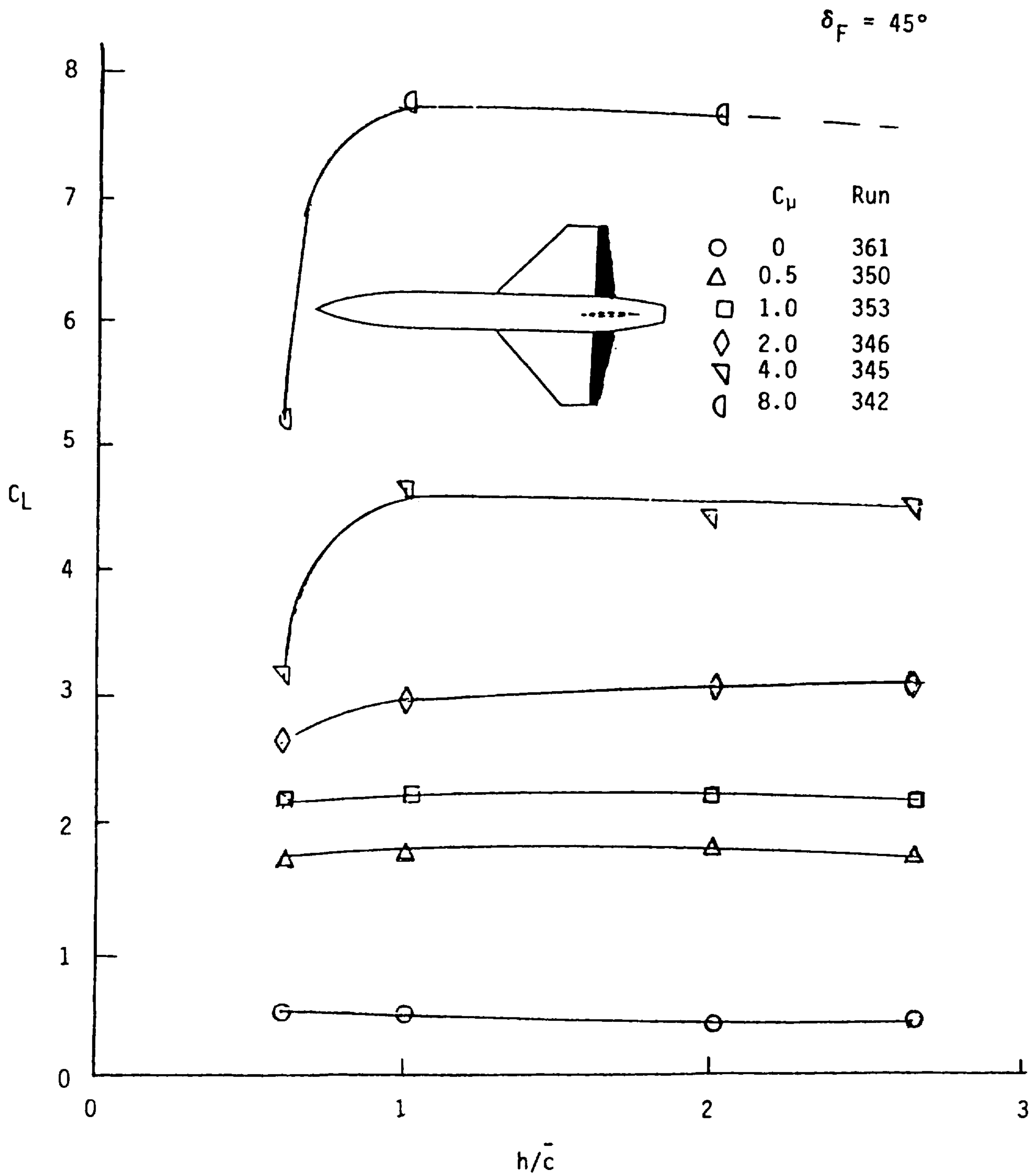


Figure 28. Effect of Ground Proximity on Lift Coefficient

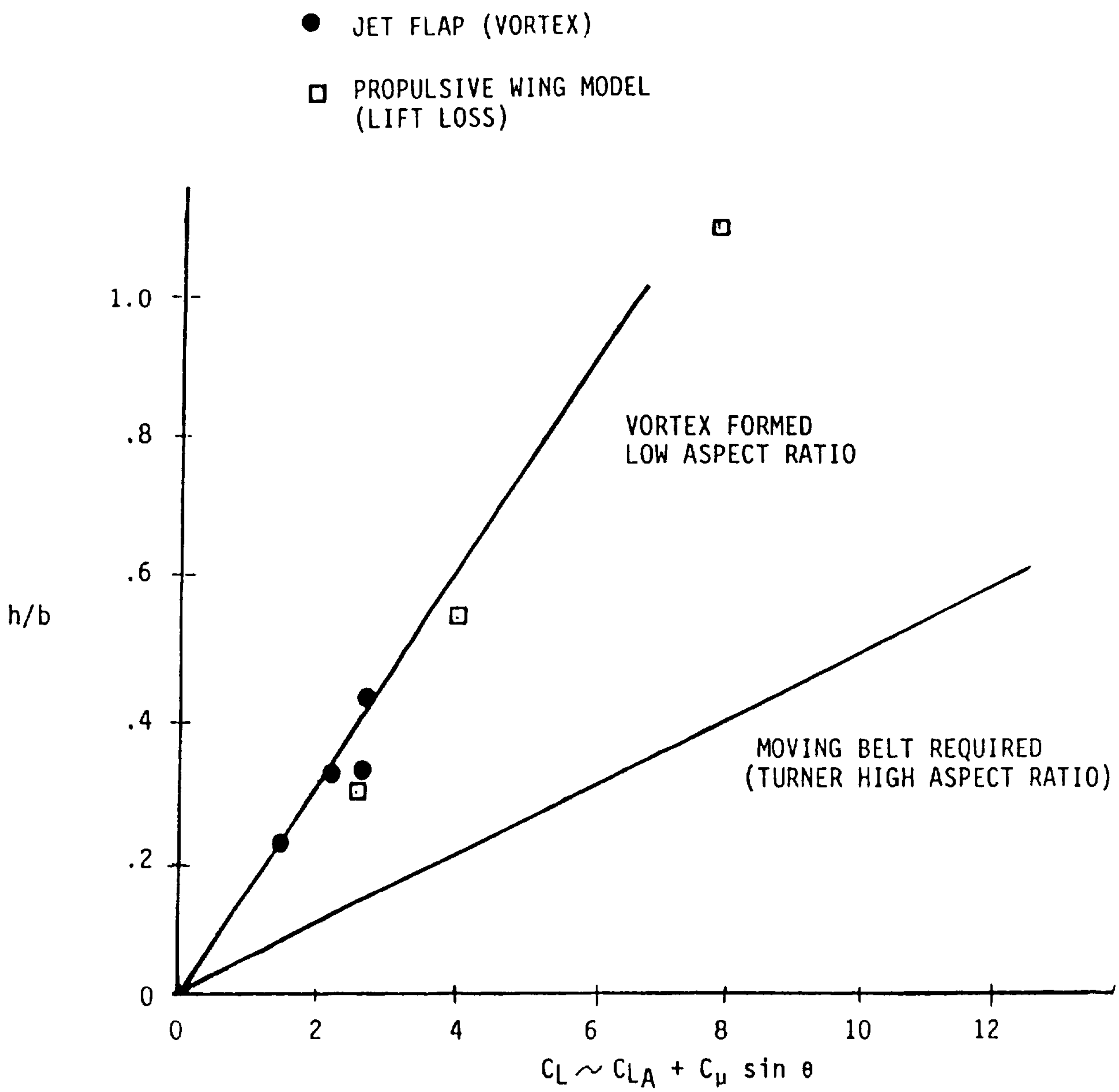


Figure 29. Requirement for a Moving Ground Board